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Mean COAMPS Air-Sea Fluxes over the Mediterranean during 1999

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14. ABSTRACT

Temporally and spatially averaged air-sea fluxes for the Mediterranean Sea were computed from surface fields output by COAMPS reanalyses conducted for the year 1999. The COAMPS air-sea fluxes were compared with climatological values computed by May (1986) from GOADS observations and with some other estimates.

The mean windstress fields output by COAMPS for 1999 are fairly consistent with the climatological windstresses in both magnitude and direction, and there is good agreement between COAMPS and the climatology for the main wind features. The pattern of the mean surface heat flux from COAMPS for 1999 is consistent with the climatology in terms of generally higher net cooling in the northern Mediterranean than in the south, and stronger cooling in the areas of stronger mean winds. However, the COAMPS mean total heat flux for the Mediterranean for 1999 (-37 W/m^2) is lower than the mean estimated from the Gibraltar inflow (-7 W/m^2) and is outside estimates of the interannual range of the annual mean surface heat flux (-25 to 15 W/m^2).

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1. INTRODUCTION

Air-sea fluxes from the atmospheric component of the Coupled Ocean/Atmosphere Mesoscale Prediction System COAMPS[1] (Hodur 1997) are being used for ocean modeling studies in the Mediterranean. The purpose of this report is to compute and document both temporally averaged and temporally and spatially averaged values of the COAMPS air-sea fluxes over the Mediterranean during 1999, to compare the averaged fluxes with climatological fluxes, and to look at some of the properties of the averaged fluxes.

The COAMPS atmospheric modeling system consists of both atmospheric analysis and forecast models and is run regularly at the Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) on an 81-km resolution grid over Europe, with a nested grid of 27-km resolution over the Mediterranean. The larger 81-km grid is itself nested within the Navy Operational Global Atmospheric Prediction System (NOGAPS), which has a resolution of about 100 km. This report looks at air-sea fluxes from the 27-km COAMPS model, which is the highest resolution COAMPS grid that covers the entire Mediterranean.

The COAMPS fields that are used here are not from the real-time operational COAMPS runs, but are from a reanalysis of the meteorological fields over Europe and the Mediterranean that is being conducted for the period October 1998 to the present using the most recent version of COAMPS and all available data. The advantages of the reanalysis over the real-time COAMPS runs are that the most recent atmospheric analysis and forecast models are used for the entire period of the reanalysis and some additional data that were not available for the operational runs can be included.

The climatological air-sea flux estimates of May (1986) for the Mediterranean Sea are presented to provide comparison with the COAMPS time-averaged fluxes. Since the Mediterranean is almost a closed basin, the long-term mean surface heat flux is small. Based on the temperatures of the inflow and outflow through the Strait of Gibraltar, the long-term mean heat gain of the Mediterranean from surface heat fluxes is estimated to be about -7 W/m^2 (Bethoux 1979, Macdonald et al. 1995). Garrett et al. (1993), working with 42 years of Comprehensive Ocean Atmosphere Data Set (COADS) data from 1947 to 1988, estimated the year-to-year variability of the annual mean heat flux over this 42-yr period to be in the range of -25 to 15 W/m^2. This estimate of the range of the annual-mean heat flux provides some constraint on the possible deviation of the COAMPS heat fluxes for a particular year from the long-term mean.

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[1]COAMPS^{TM} is a trademark of the Naval Research Laboratory.

Latent and sensible heat fluxes were also computed from COAMPS wind speed, air temperature, humidity, and sea-surface temperature (SST) using bulk formulas. Time-averaged values of these fluxes are compared with the latent and sensible heat fluxes output from COAMPS. Ocean models frequently use bulk formulas and their own predicted SST to compute their input latent and sensible heat fluxes when there is no feedback of the ocean model SST to the atmospheric model (which is usually the way the ocean models are run). This is done to provide feedback between the surface heat flux and the ocean model SST to reduce drift of the ocean model SST due to biases in either the surface heat fluxes or the ocean model itself.

The sections that follow include: (2) a discussion of the climatological windstresses and heat fluxes of May (1986); (3) a discussion of the time-averaged COAMPS fluxes; (4) a discussion of the time-averaged latent and sensible heat fluxes computed from the COAMPS fields using bulk formulas; and (5) a summary. Most of the figures showing seasonally averaged fields for Sections 2 – 4 are in Appendices A through C at the end of the report (to reduce the clutter of a large number of figures within the main body of the report). All of the figures have the x and y axes labeled with longitude in °E and latitude in °N, respectively.

2. CLIMATOLOGICAL AIR-SEA FLUXES OF MAY (1986)

May (1982, 1986) computed climatological air-sea flux estimates for the Mediterranean from COADS data. The fluxes were computed from the individual observations as monthly averages on 1-degree latitude-longitude squares. May (1982) discusses the calculation of mean windstresses from the COADS data, and presents the monthly and annual mean windstresses that were computed.

May (1986) provides a brief summary of the procedure used to calculate mean heat fluxes from the COADS data and also to recalculate the mean windstresses (there were some small changes to the procedure used in the 1982 study). Seasonal averages of these data, which are referred to here as the M86 data, are presented in Appendix A. The seasonally averaged fields in Appendix A are vector windstress, windstress magnitude, windstress curl, solar radiation, longwave radiation, latent heat flux, sensible heat flux, and total surface heat flux.

Figure 1 shows the annual mean of the M86 windstress. The mean windstress is eastward to southeastward over most of the Mediterranean, but is to the southwest in the Adriatic and Aegean Seas. Strong wind features that can readily be seen are the mistral winds in the Provencal Basin in the northwestern Mediterranean, the bora winds in the northern Adriatic Sea, and the etesian winds blowing out of the Aegean Sea. The mistral and bora winds are strongest in fall and winter (Fig. A1).

Figure 2 shows the curl of the annual mean M86 windstress. Windstress curl has a significant influence on the near-surface currents in ocean models due to the divergence or convergence of the wind-driven Ekman transport and the resulting surface pressure gradient, which drives the upper-ocean geostrophic currents. Regions of positive windstress curl cause divergence of the Ekman transport, which results in upwelling of colder water from below, a local "low" of the surface elevation, and cyclonic currents. Regions of negative windstress curl have the opposite effect. Ocean currents sometimes follow lines of zero windstress curl since this is a boundary between an area of upwelling and downwelling, which tends to create a horizontal density gradient normal to the windstress curl line, which in turn can drive a geostrophic current.

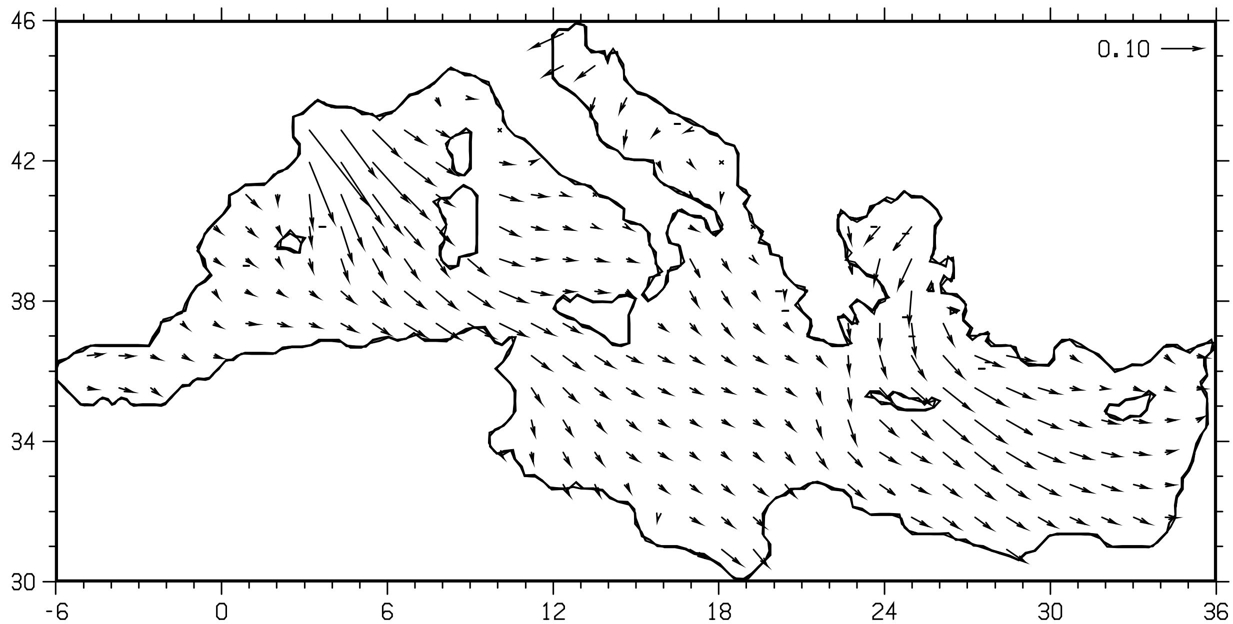

Fig. 1 — Annually averaged climatological windstress (in Pascals)

With these tendencies in mind, the windstress curl in Fig. 2 reflects a number of features of the Mediterranean circulation. For example, in the Tyrrhenian Sea, the area of positive windstress curl east of Corsica and the small area of negative windstress curl east of Sardinia reflect cyclonic and anticyclonic circulations that are observed there. These are theorized to be driven by the eastward wind flowing through the Bonifacio Strait between Sardinia and Corsica (Astraldi et al. 1995).

The area of positive windstress curl southwest of Crete is in the location of the cyclonic Cretan eddy. The area of negative windstress curl southeast of Crete is in the location of the anticyclonic Ierapetra eddy (Robinson et al. 1991). It is thought that these two eddies are driven by the east-west gradient in the windstress south of the east and west ends of Crete caused by the blocking effect of the island of Crete on the southward-blowing winds.

The line of zero windstress curl along the African coast in the western Mediterranean and passing through the Straits of Sicily and into the Ionian Sea in the eastern Mediterranean lies roughly along the path of the Algerian and Ionian currents, respectively.

Figure 3 shows the annual mean of the M86 total surface heat flux. There is generally a net heat loss in the northern Mediterranean and a net heat gain in the south. The calculation of these heat fluxes was adjusted by May (1986) to yield an area-averaged annual mean heat flux over the Mediterranean of about -7 W/m^2 (Table 2), which is roughly the mean heat flux needed to balance the net heat gained from the inflow and outflow through the Strait of Gibraltar (Bethoux 1979). The fact that the long-term mean surface heat loss over the Mediterranean needs to approximately balance the net heat gained through the Strait of Gibraltar provides a very useful constraint on attempts to calculate the surface heat fluxes over the Mediterranean.

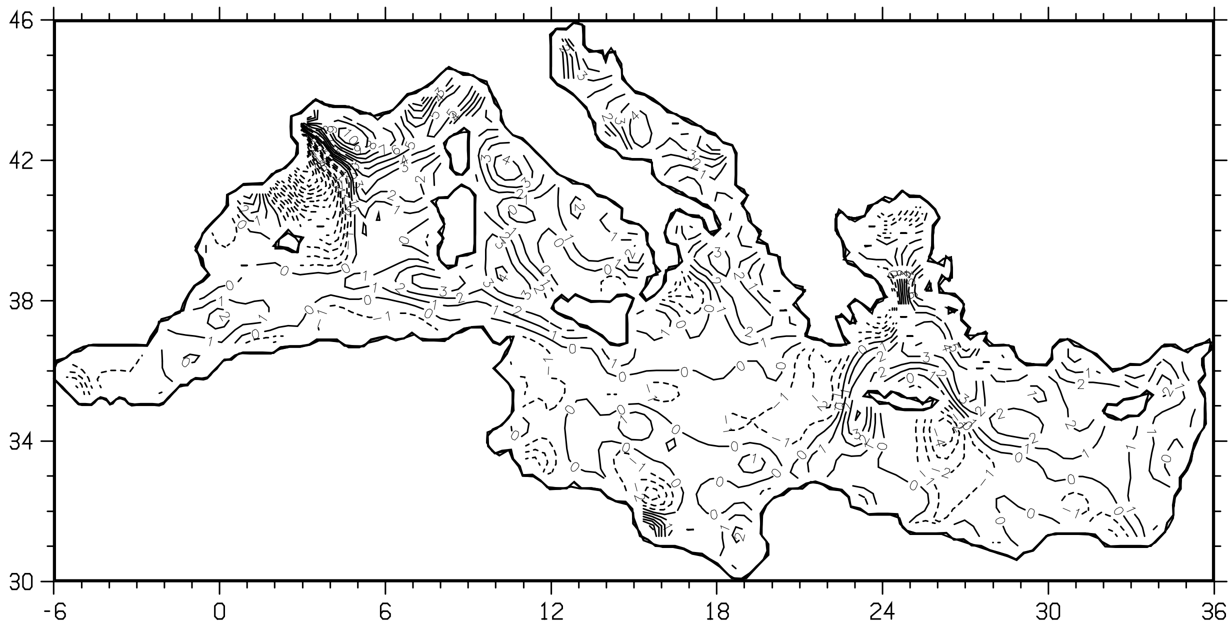

Fig. 2 — Annually averaged climatological windstress curl (contour interval is 1 Pascal per 10000 km)

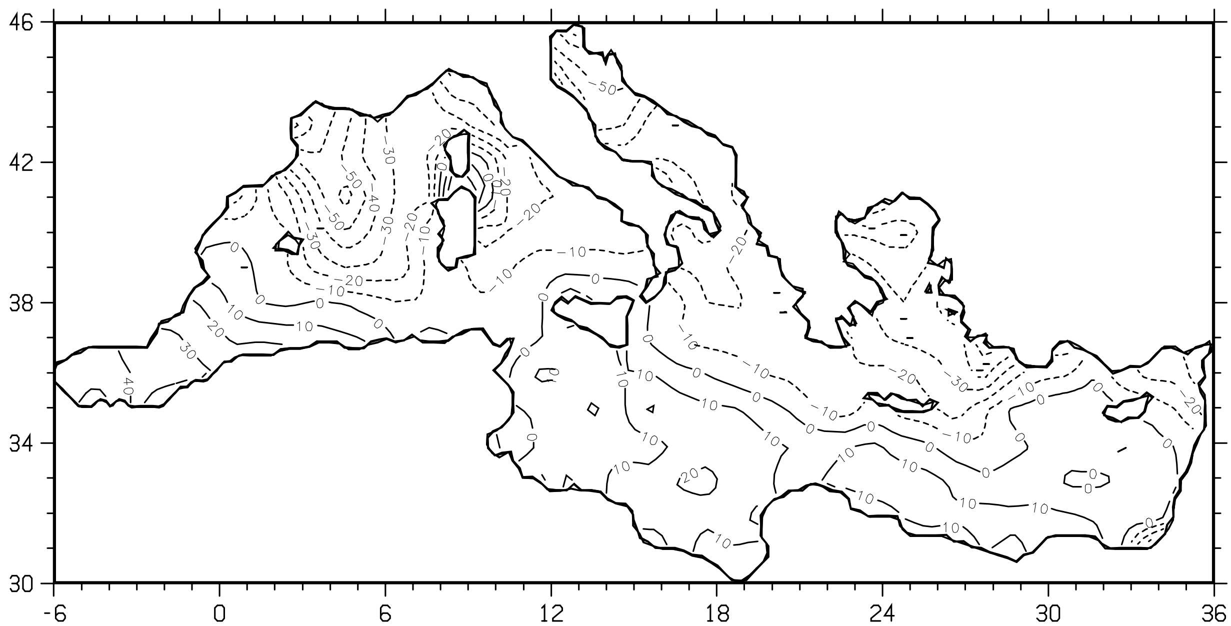

Fig. 3 — Annually averaged climatological total surface heat flux (contour interval is 10 W/m^2)

3. MEAN COAMPS AIR-SEA FLUXES DURING 1999

The COAMPS atmospheric model is currently run with a 12-h update cycle. This means that analyses are done every 12 h, atmospheric forecasts are initialized from these analyses, and the forecast fields at 12 h are used for input to the next analysis. Forecast fields from COAMPS are output and archived at 1-h intervals.

The COAMPS fields that are investigated here are the hourly fields output from the COAMPS Mediterranean 27-km resolution Lambert conformal grid during the first 11 h of each forecast (i.e., the analysis fields at the start of the forecast and the fields at each forecast hour up to 11 h from the start of the forecast). COAMPS forecasts on the Mediterranean 27-km grid are performed regularly at FNMOC in Monterey, CA, to support Navy operations in the Mediterranean. However, the COAMPS fields that are analyzed here were computed during a special meteorological reanalysis effort for the Mediterranean. This reanalysis is being done by recomputing meteorological forecasts for this area using the latest version of COAMPS and all available data to provide an hourly timeseries of high-resolution, meteorological fields from October 1998 to the present.

For the analyses done here, the COAMPS fields were bilinearly interpolated (bicubic polynomial interpolation was used for windstress to maintain smooth gradients) to a 20-km latitude-longitude grid. The hourly fields were time-averaged to compute seasonal and annual means. Appendix B provides plots of the seasonal means for the COAMPS surface air pressure, surface windstress vectors, windstress magnitude, windstress curl, solar radiation, longwave radiation, latent heat flux, sensible heat flux, total surface heat flux, evaporation, precipitation, and total surface moisture flux (evaporation minus precipitation).

Figure 4 shows the COAMPS annual mean surface windstress vectors for 1999. This plot looks very similar to the M86 climatology in Fig. 1. As in the climatology, the mean windstress is east to southeast over most of the Mediterranean, with southwest mean windstress in the northern Adriatic and Aegean. Comparison with Fig. 1 suggests that the COAMPS mean windstress magnitude generally is a bit less than the M86 climatology, and this is shown by the area-averaged windstress vector magnitude, which is listed in Table 1.

Table 1 — Climatological (M86) and COAMPS Area-mean Windstress Magnitude (in Pascals).

Season	M86	COAMPS
Winter	0.062	0.057
Spring	0.033	0.034
Summer	0.041	0.034
Fall	0.054	0.046
Annual	0.044	0.039

Figure 5 shows the COAMPS annual mean surface windstress curl for 1999. It is significantly noisier than the M86 climatology in Fig. 2. A noisier field might be expected for a shorter-term average, especially for a field computed as a gradient. The most noticeable feature of the COAMPS windstress curl is the large values near the coastlines. COAMPS typically predicts large gradients in the surface winds near coasts due to coastal orography and to significant differences between

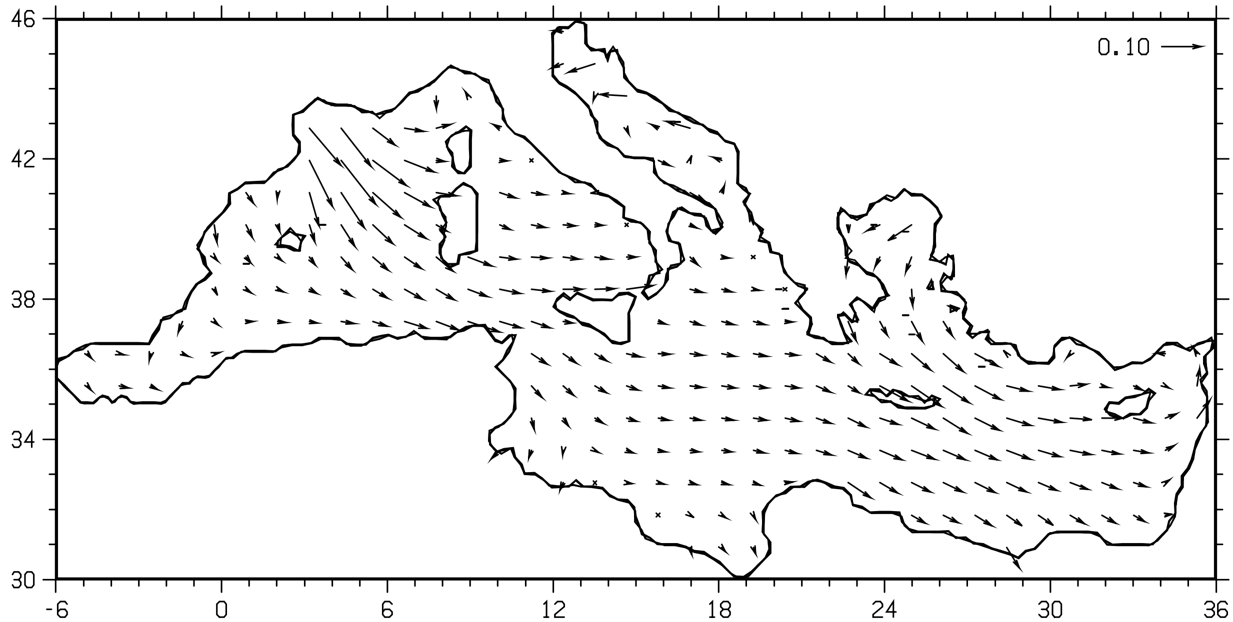

Fig. 4 — Annual mean COAMPS surface windstress during 1999 (in Pascals)

the surface atmospheric boundary layer over the land and the boundary layer over the sea. There tends to be a significantly larger increase in the daytime surface temperature due to solar heating over land than over water, and this causes greater instability and mixing in the surface atmospheric boundary layer. This, in turn, affects the strength of the near-surface winds.

Some features seen in the M86 windstress curl are not observed in the COAMPS windstress curl. The prominent patterns of positive and negative windstress curl in the M86 climatology southwest and southeast of Crete, respectively (Fig. 2), are not seen in Fig. 5. It may be that the resolution of the COAMPS Mediterranean grid (27 km) is not sufficient to resolve the blocking effect of Crete on the southward-directed winds.

Figure 6 shows the COAMPS annual mean total surface heat flux for 1999, and Table 2 compares the COAMPS and M86 area-averaged seasonal and annual mean heat fluxes. The table includes the total heat flux and the solar, longwave, latent, and sensible components of the total heat flux.

The COAMPS area-averaged annual mean total surface heat flux for 1999 is -37 W/m^2. This is significantly lower than the climatological mean heat flux of about -7 W/m^2 estimated from the temperature of the Gibraltar inflow and outflow (Bethoux 1979, Macdonald et al. 1995), and is outside the range of the annual mean heat flux of -25 to 15 W/m^2 computed by Garrett et al. (1993) from 42 years of COADS data.

Table 2 shows that all four heat flux components contribute to the COAMPS total heat flux being lower than the climatology, although the largest contributions come from the latent and sensible heat fluxes. On a seasonal basis, the COAMPS total heat flux is lower than the climatology in all seasons, although the largest differences are in summer and fall. Based on the constraint on the

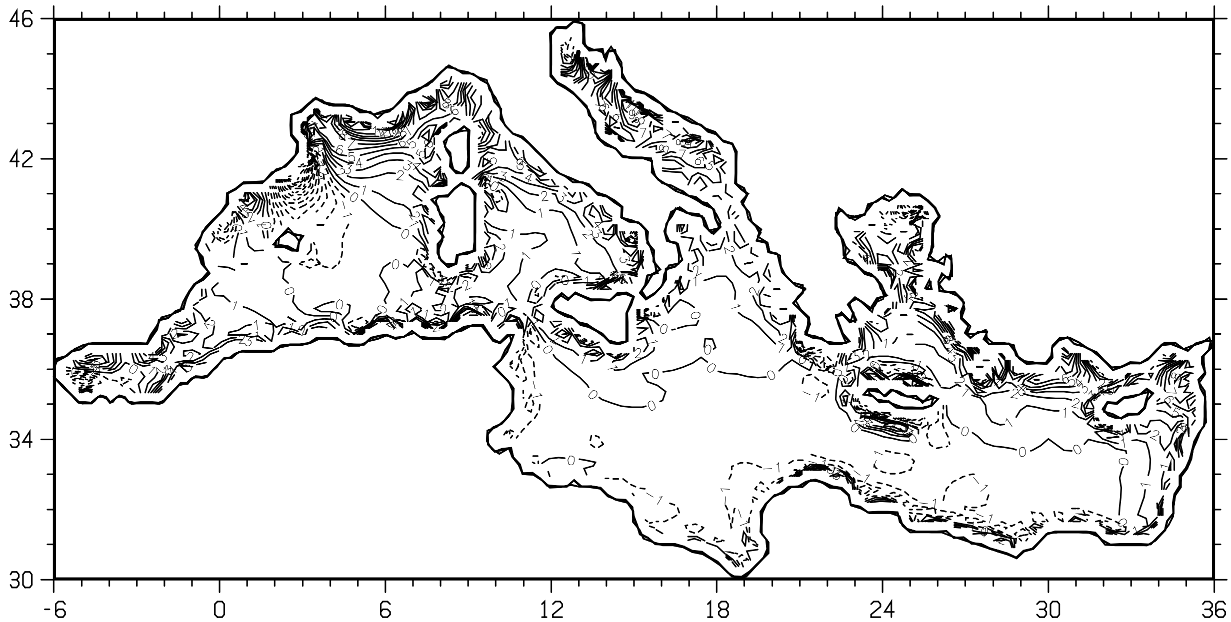

Fig. 5 — Annual mean COAMPS surface windstress curl during 1999 (contour interval is 1 Pascal per 10000 km)

long-term mean total heat flux of the Gibraltar inflow/outflow and the estimate of the interannual range of the total surface heat flux by Garrett et al. (1993), it seems likely that the COAMPS mean total surface heat flux for 1999 is too low.

Previous estimates of the surface heat fluxes in the Mediterranean using bulk formulas (Bunker et al. 1982, Garrett et al. 1993, Gilman and Garrett 1994) found that bulk formulas overestimated the surface cooling in the Mediterranean by about 30 W/m^2 (Send et al. 1999). Gilman and Garrett (1994) thought that the discrepancy might be due to the effect of atmospheric aerosols.

The plot of the COAMPS total surface heat flux (Fig. 6) shows net cooling everywhere, whereas the M86 climatology shows net cooling in the north and net warming in the south (Fig. 3). However, the pattern of the net heat fluxes is similar, with stronger cooling in the north than in the south and strong cooling in the high wind areas of the northwest Mediterranean and the northern Adriatic and Aegean Seas.

A notable feature in the plot of the COAMPS total surface heat flux is the area of strong cooling southeast of Crete in the area of the anticyclonic Ierapetra eddy. This area of increased heat loss seems to be mainly due to the warm SST in this area that occurs in the COAMPS SST analyses (Fig. C3), which must be a reflection of the presence of the eddy. The Ierapetra eddy seems to be one of the more consistent features of the eastern Mediterranean seen in satellite SST and SSH observations, e.g., it can be seen in the NOAA AVHRR image on the cover of the special issue on the south Aegean Sea of the journal, *Progress in Oceanography* (Angel and Smith 1999).

There are suggestions of the anticyclonic Alboran gyres in Fig. 6 in the Alboran Sea near Gibraltar. However, the increased net cooling in this area may reflect more the larger windspeeds along the axis of the Alboran Sea (Fig. C1) than higher SSTs (Fig. C3).

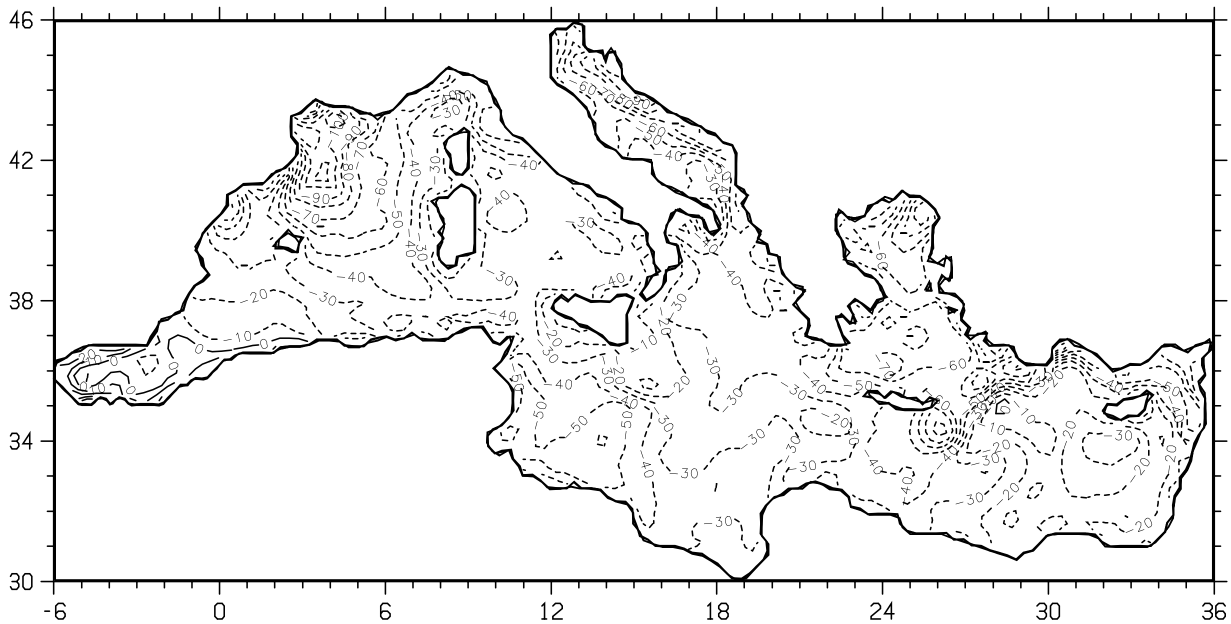

Fig. 6 — Annual mean COAMPS total surface heat flux during 1999 (contour interval is 10 W/m^2)

Table 2 — Climatological (M86) and COAMPS 1999 (COA) Area-mean Surface Heat Fluxes (in W/m^2). Solar and Total Surface Heat Fluxes Are Positive Downwards, Others Are Positive Upwards.

	Solar		Longwave		Latent		Sensible		Total	
Season	M86	COA	M86	COA	M86	COA	M86	COA	M86	COA
Winter	123	117	71	75	122	123	20	30	-90	-112
Spring	253	270	64	69	70	75	0	10	119	115
Summer	256	245	65	71	111	124	3	13	77	37
Fall	110	92	72	78	151	172	21	32	-135	-190
Annual	185	181	68	73	113	123	11	22	-7	-37

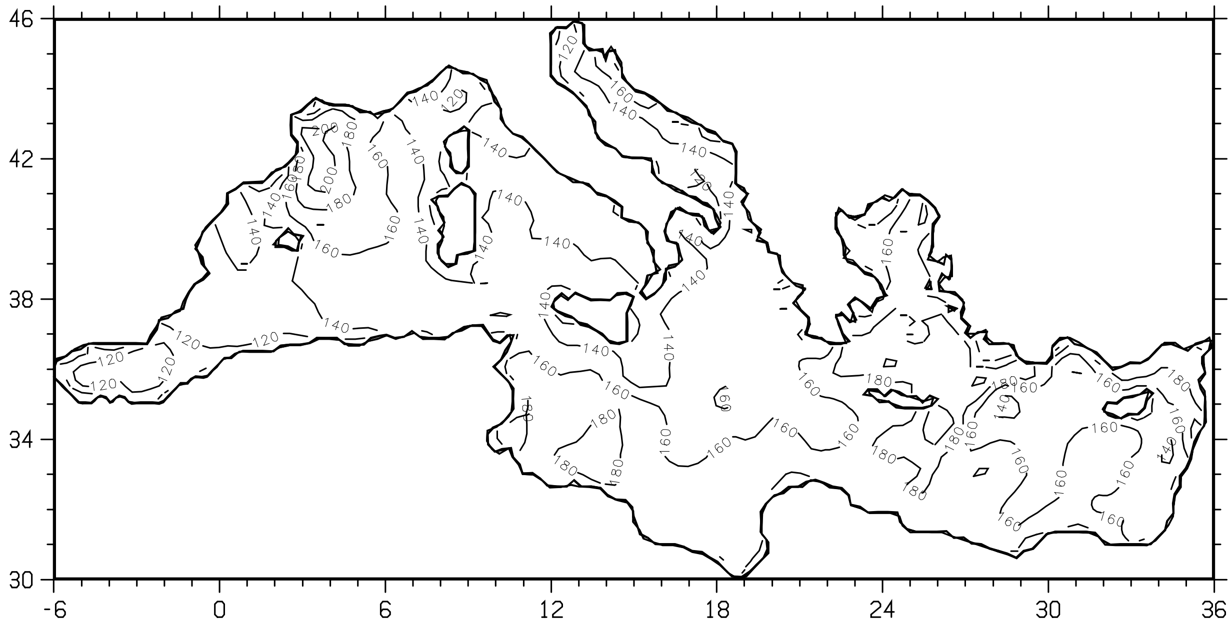

Fig. 7 — Annual mean COAMPS evaporation during 1999 (contour interval is 20 cm/yr)

Figures 7, 8, and 9 show the COAMPS annual mean surface evaporation, precipitation, and moisture flux (evaporation minus precipitation), respectively, for 1999. The area-averaged seasonal and annual mean COAMPS moisture fluxes for 1999 are listed in Table 3.

Table 3 — M86 COAMPS Area-mean Evaporation and Precipitation (in cm/yr).

Season	Evaporation	Precipitation	Evap−Precip
Winter	155	64	91
Spring	93	17	76
Summer	155	28	127
Fall	216	75	141
Annual	155	46	109

The COAMPS surface evaporation is derived from the latent heat flux. The largest evaporation tends to occur where the winds are strong or the air is relatively dry. Hence, the evaporation is strong in the northwest Mediterranean in the Provencal Basin and in the northeast Adriatic due to the strong mistral and bora winds. The annual mean COAMPS evaporation for 1999 is 155 cm/yr, and the strongest evaporation occurs in the fall (Table 3), even though the mean windstress magnitude is larger in the winter (Table 1).

Figure 8 shows the COAMPS annual mean precipitation for 1999, and the seasonal and annual area averages are listed in Table 3. The COAMPS annual mean precipitation rate for 1999 is 46 cm/yr (Table 3). The precipitation is highest in the north-central Mediterranean along the Italian coast, in the Adriatic Sea, and in the northeastern Mediterranean off the coasts of Turkey, Syria, and Lebanon (Fig. 8).

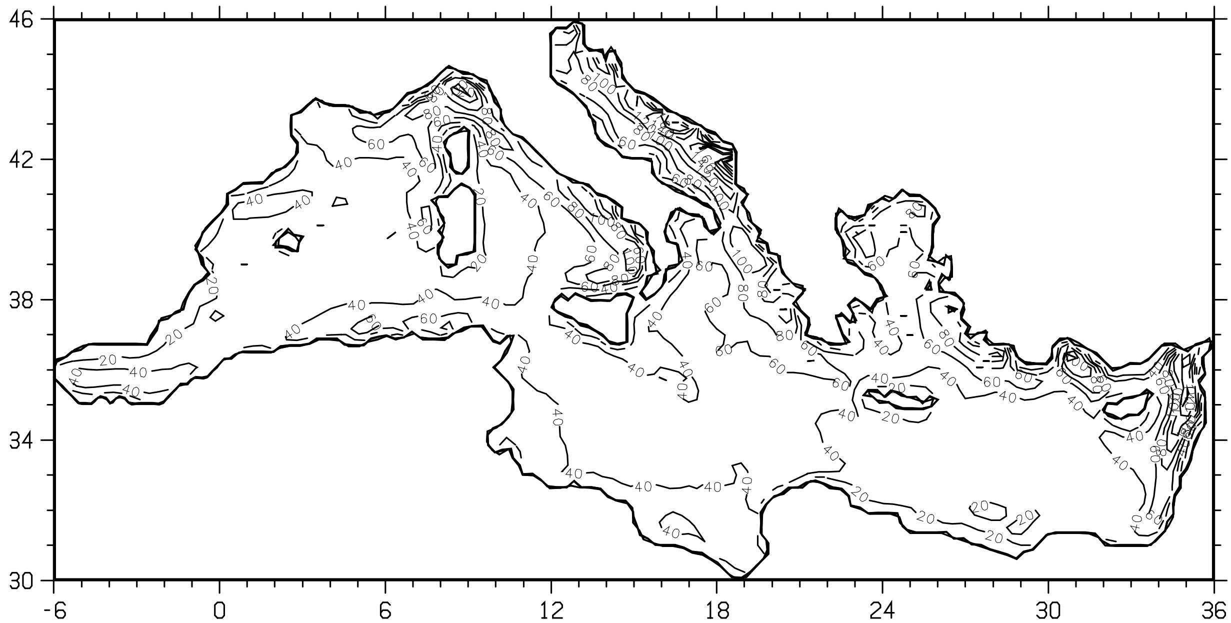

Fig. 8 — Annual mean COAMPS precipitation during 1999 (contour interval is 20 cm/yr)

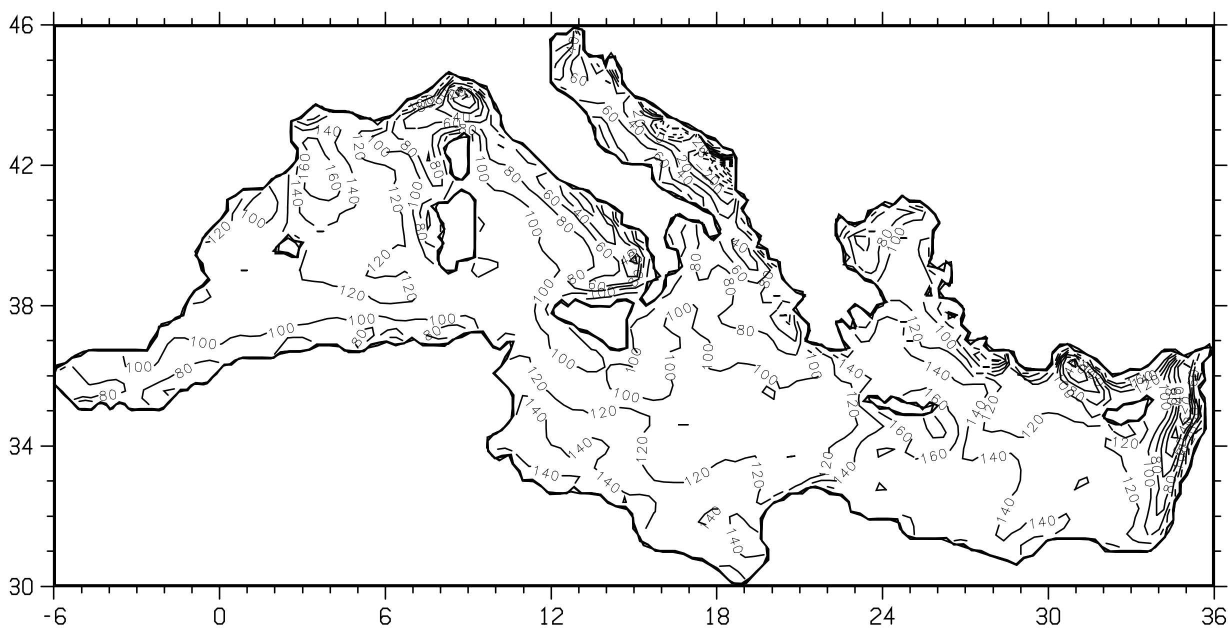

Fig. 9 — Annual mean COAMPS evaporation minus precipitation during 1999 (contour interval is 20 cm/yr)

The COAMPS mean surface moisture flux (evaporation minus precipitation) for the Mediterranean for 1999 is 109 cm/yr (Table 3). This is higher than most estimates of the mean surface moisture flux for the Mediterranean, which range from 40 to 95 cm/yr (Astraldi 1999). Table 4 lists some of these estimates. Most of the estimates lie in the range of 58 to 63 cm/yr.

Table 4 — Estimates of the Mean Surface Moisture Flux (Evaporation minus Precipitation) over the Mediterranean from Several Sources (in cm/yr).

Source	Moisture Flux
Bethoux (1979)	95
Peixoto (1982)	63
Bryden et al. (1988)	58
Bryden and Kinder (1991)	60
Garrett et al. (1993)	60
Harzallah et al. (1993)	40

The time-averaged surface moisture flux must balance the net inflow into the Mediterranean, which is mainly the net inflow through Gibraltar Strait (the mean inflow from the rivers is only about 0.01 Sv). By multiplying by the total surface area of the Mediterranean (about 2.53×10^6 km^2), the surface moisture flux can be converted to a flowrate of 0.088 Sv (1 Sv = 10^6 m^3/s). This is about 10% of the total mean Gibraltar inflow into the Mediterranean, which is estimated to be about 0.9 Sv (Bryden and Kinder 1991).

4. MEAN LATENT AND SENSIBLE HEAT FLUXES COMPUTED FROM COAMPS ATMOSPHERIC FIELDS WITH BULK FORMULAS

When heat fluxes are specified to an ocean model without feedback from the ocean model, there are usually problems with heating and cooling biases in the heat fluxes such that the ocean heats or cools too much over a period of time. This can especially be a problem in shallow water where the thermal inertia of the water column is small and biases in the surface heat fluxes are quickly felt. Some fixes for this problem are to add an additional corrective heat flux to the ocean model based on the difference between the model SST and some specified SST, or to provide a correction directly to the ocean model upper-layer temperature.

Another approach to reducing bias in surface heat fluxes is to compute air-sea heat fluxes using bulk formulas and the ocean model SST so that there is feedback between the predicted SST and the heat fluxes (Kara et al. 2000). To compute the latent and sensible heat fluxes using standard bulk formulas, the other parameters needed are the surface air pressure, the near-surface air temperature and wind speed, and some measure of the near-surface humidity. These fields can be obtained from the output of an atmospheric model.

Note that with the use of heat fluxes computed using the ocean-model SST and surface fields from an atmospheric model, there will be a tendency to drive the ocean-model SST toward the SST that was used by the atmospheric model when it was run. However, this tendency can be outweighed by other factors and may not necessarily prevail, especially on short timescales.

Latent and sensible heat fluxes for the Mediterranean for 1999 were computed using standard bulk formulas and hourly values of air pressure, air temperature, wind speed, and relative humidity output by the 27-km COAMPS atmospheric model. For the SST, the COAMPS 12-h SST fields were used, which were derived from analyses of real-time SST observations (mostly multichannel satellite SST data). These are the SST values that were used by COAMPS when it was run. This SST field was computed every 12 h at the start of each atmospheric forecast cycle and was held constant during the atmospheric forecast.

The drag coefficient used with the bulk formulas to calculate the latent and sensible heat fluxes was the stability-dependent formulation of Kondo (1975), with a neutral value for the coefficients of 0.0014 for the latent heat flux and 0.0011 for the sensible heat flux. These neutral values for the coefficients resulted in mean values for the computed latent and sensible heat fluxes that were in good agreement with the mean values output by COAMPS (Table 5).

Table 5 — Seasonal, Area-mean Values of COAMPS Fields Used in Calculating Latent and Sensible Heat Flux via Bulk Formulas, and Values of Latent and Sensible Heat Flux for the May Climatology (M86), for COAMPS (COA), and as Calculated Using Bulk Formulas (BLK). WIND is the Wind Speed, HUM is the Percent Humidity, and TA is the Air Temperature. Wind Speed is in m/s, Temperatures Are in °C, and Heat Fluxes Are in W/m^2, Positive Upwards.

						Latent			Sensible		
Season	WIND	HUM	TA	SST	SST-TA	M86	COA	BLK	M86	COA	BLK
Winter	6.42	73	12.2	15.2	3.0	122	123	129	20	30	31
Spring	4.85	82	17.9	19.5	1.6	70	75	79	0	10	12
Summer	4.42	80	23.8	25.9	2.1	111	124	121	3	13	14
Fall	6.03	72	17.2	20.5	3.3	151	172	171	21	32	31
Annual	5.43	77	17.8	20.3	2.5	113	123	125	11	22	22

Note that the COAMPS wind speed is at 10-m height, which is the standard height for variables used in bulk calculations of air-sea fluxes. However, the COAMPS air temperature and humidity are at 2-m height. In computing the heat fluxes using the bulk formulas, no correction was made for the 2-m height of the air temperature and humidity. It would be expected that adjustment of these parameters to 10-m height would typically slightly decrease the air temperature and humidity and as a result, slightly increase the heat fluxes.

Appendix C shows seasonally averaged values of the COAMPS fields used in the calculation of the latent and sensible heat fluxes: the surface wind speed, sea temperature, air temperature, sea-air temperature difference, and humidity and seasonally averaged values of the computed latent and sensible heat fluxes.

Table 5 lists the seasonal and annual means of the area-averaged values of the COAMPS fields used to compute the latent and sensible heat fluxes and a comparison of the computed fluxes with the M86 climatology and the latent and sensible heat fluxes output by COAMPS. As noted above, the neutral values of the drag coefficients that were used result in good agreement between the latent and sensible heat fluxes computed using bulk formulas and the values output by COAMPS. The spatial distribution also shows good agreement, as can be seen by comparing Fig. C6 with

Fig. B7 for the seasonally averaged latent heat fluxes and Fig. C7 with Fig. B8 for the seasonally averaged sensible heat fluxes.

5. SUMMARY

Temporally and spatially averaged air-sea fluxes for the Mediterranean Sea are computed from surface fields output by COAMPS reanalyses for the year 1999. The reanalyses were run on an 81-km grid covering Europe and North Africa, with a 27-km nested grid centered over and covering the Mediterranean. The averaged COAMPS air-sea fluxes from the 27-km Mediterranean grid are compared with climatological values computed by May (1986) from COADS observations and with some other estimates.

The mean windstress fields output by COAMPS for 1999 are fairly consistent with the climatological M86 windstresses in both magnitude and direction. There is good agreement between COAMPS and the M86 climatology for the notable wind features of the northern Mediterranean, i.e., the mistral in the Provencal Basin, the bora in the northern Adriatic, and the etesian in the Aegean. The mean magnitude of the COAMPS windstress, averaged over the Mediterranean for the whole year, is about 0.039 Pascals vs 0.044 Pascals for the M86 climatology.

The windstress curl computed from the mean COAMPS windstress does not show some of the small features seen in the M86 climatology, e.g., the positive and negative curl patterns observed off the southwest and southeast corners of Crete, respectively. These windstress curl patterns are thought to be due to the blocking effect of Crete on southward directed winds and are probably the cause of the ocean circulation gyres that are sometimes seen in these locations. It may be that additional grid resolution is needed for COAMPS to reproduce these kind of features.

The pattern of the net surface heat flux from COAMPS for 1999 is consistent with the M86 climatology in terms of generally higher net cooling in the northern Mediterranean than in the south, and stronger cooling in the areas of stronger mean winds in the northwestern Mediterranean, the northern Adriatic, and the Aegean. However, the COAMPS mean total heat flux for the Mediterranean for 1999, which is -37 W/m^2, is significantly lower than the mean of about -7 W/m^2 estimated from consideration of the net heat flux through Gibraltar Strait, and is outside the estimated range of the annual mean surface heat flux (-25 to 15 W/m^2) computed by Garrett et al. (1993) from 42 years of COADS data. Hence, the COAMPS net heat flux over the Mediterranean for 1999 appears to show a bit too much cooling.

The COAMPS mean surface moisture flux for 1999 is 109 cm/yr, which is the difference between the mean evaporation rate (155 cm/yr) and the mean precipitation rate (46 cm/yr). Consistent with the COAMPS heat flux, this is a bit higher than most previous estimates, which range from 40 to 95 cm/yr.

Latent and sensible heat fluxes were calculated using bulk formulas and COAMPS surface wind speed, air temperature, humidity, and pressure fields for the Mediterranean for 1999. This was done to test the concept of using bulk calculations of these heat fluxes for one-way ocean model coupling to provide feedback from the ocean model predicted SST to the heat fluxes to reduce biases. The Kondo (1975) drag coefficient parameterization was used in the bulk formulas. The bulk calculation of the fluxes was similar to the fluxes output by COAMPS for values of the neutral drag coefficient of 0.0014 for the latent heat flux and 0.0011 for the sensible heat flux.

6. ACKNOWLEDGMENTS

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Appendix A

SEASONALLY AVERAGED CLIMATOLOGICAL AIR-SEA FLUXES OF MAY (1986)

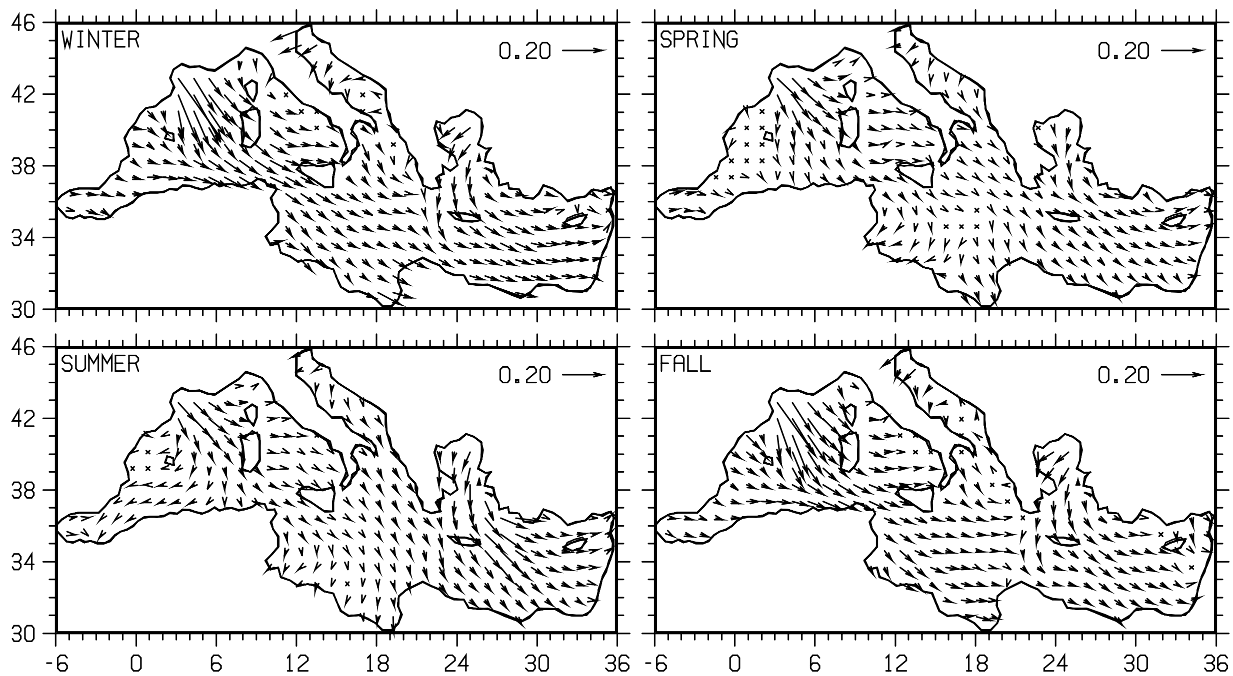

Fig. A1 — Seasonally averaged climatological wind stress (in Pascals)

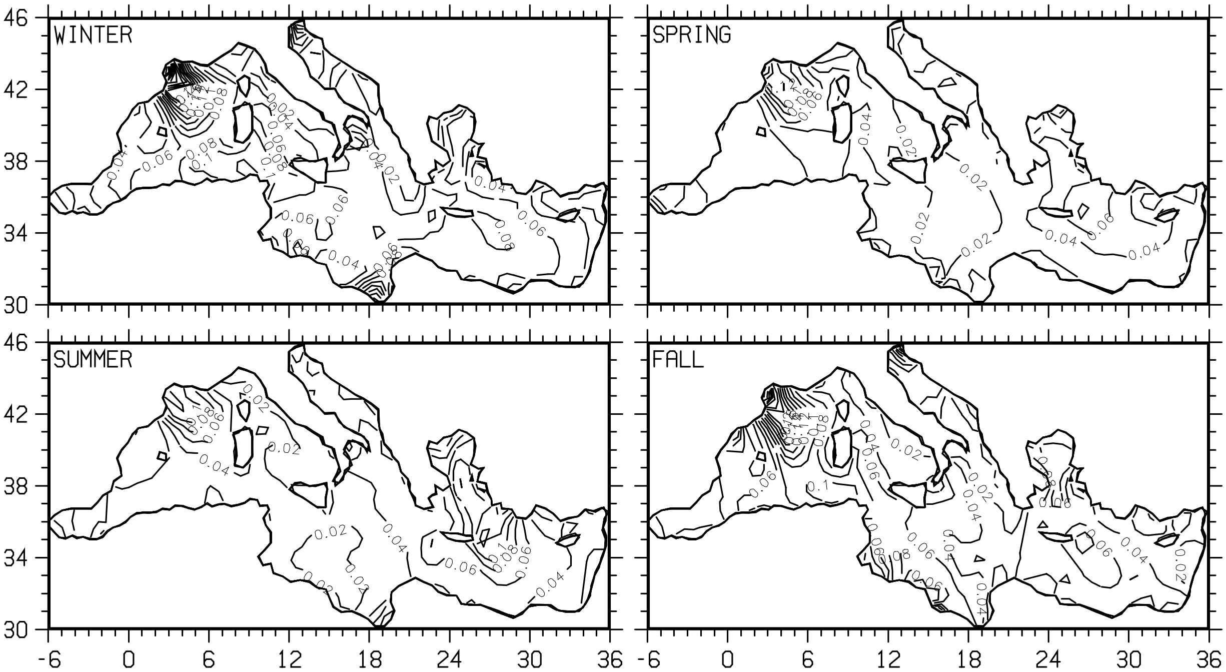

Fig. A2 — Seasonally averaged climatological windstress magnitude (contour interval is 0.02 Pascals)

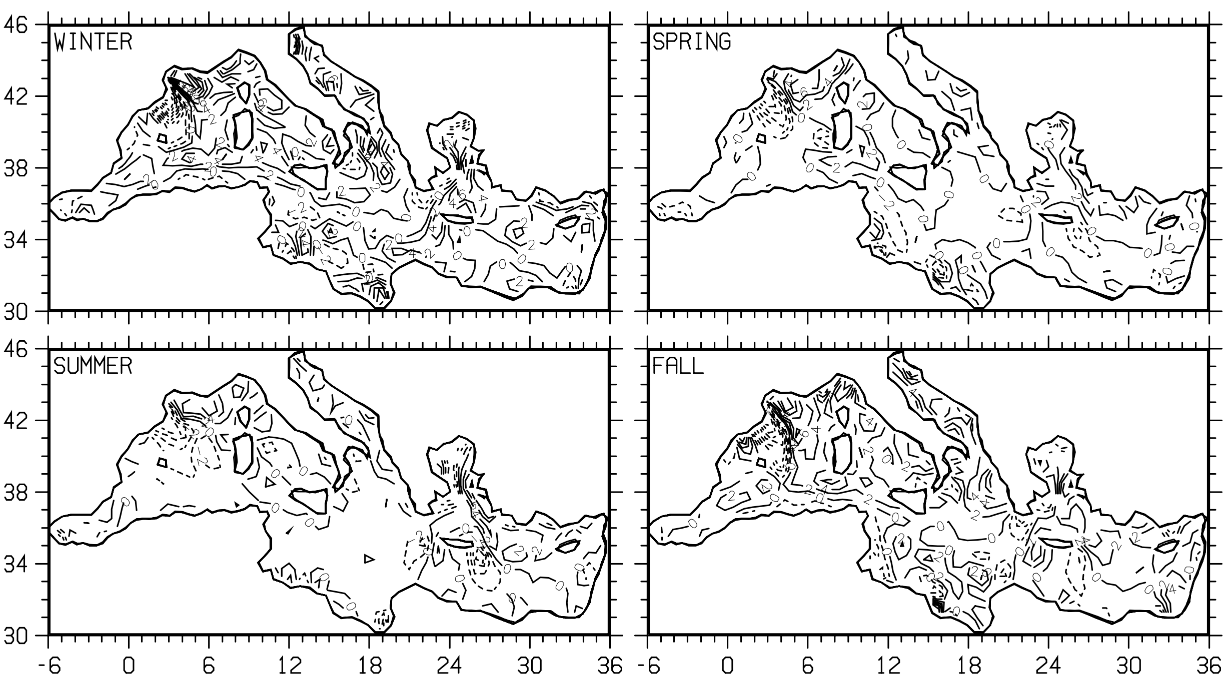

Fig. A3 — Seasonally averaged climatological windstress curl (contour interval is 2 Pascals per 10000 km)

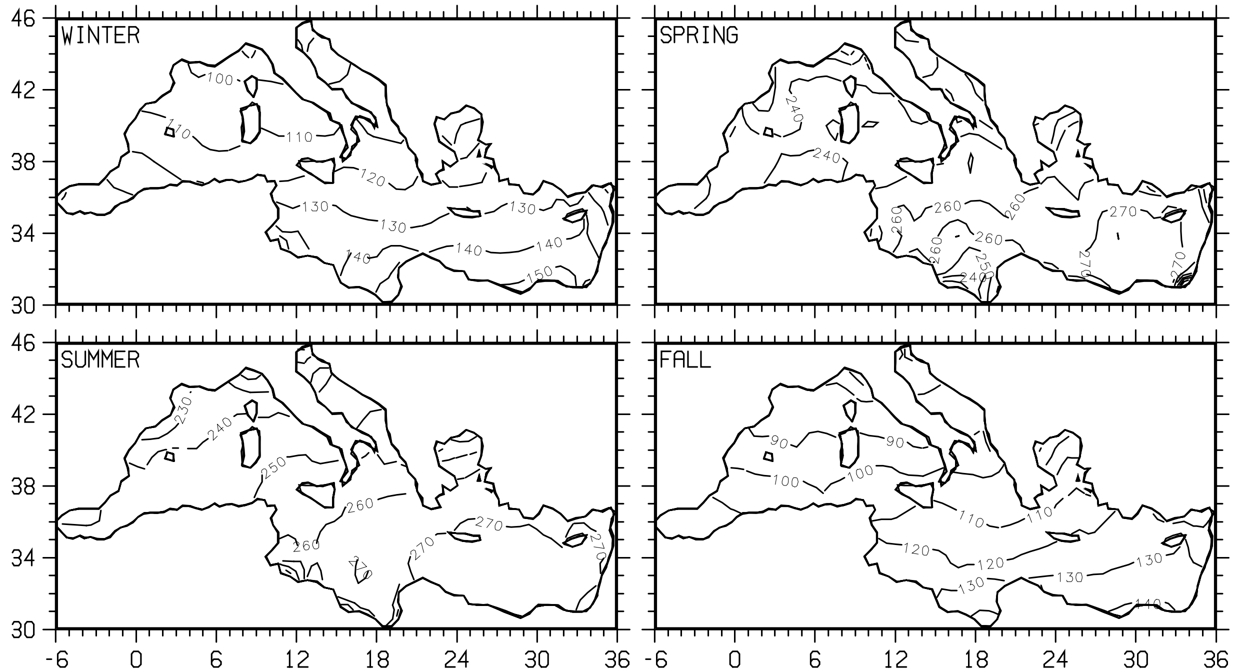

Fig. A4 — Seasonally averaged climatological solar radiation (5 % albedo applied, contour interval is 10 W/m^2)

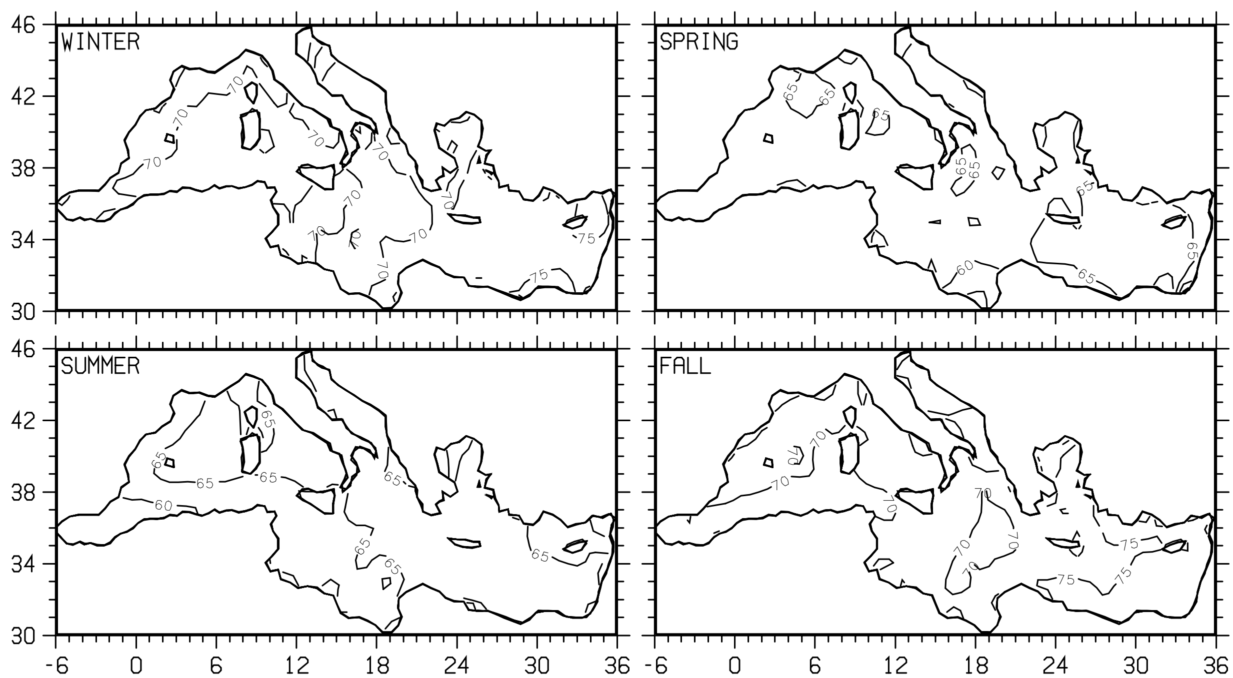

Fig. A5 — Seasonally averaged climatological longwave radiation (contour interval is 5 W/m^2)

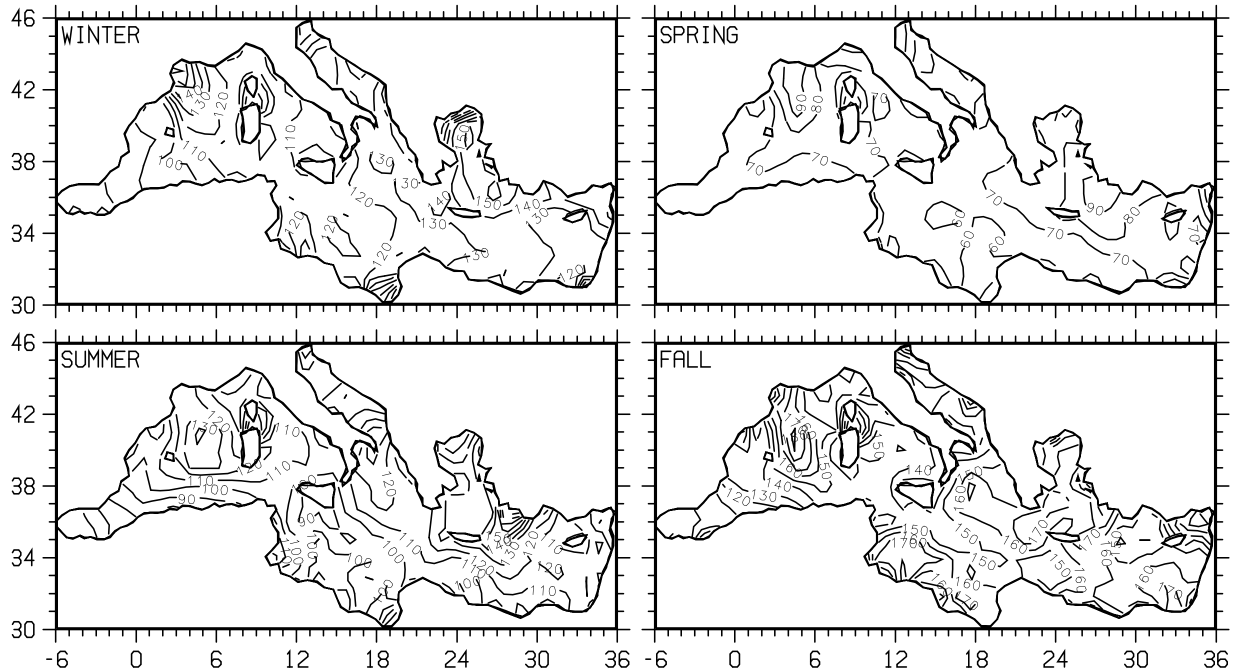

Fig. A6 — Seasonally averaged climatological latent heat flux (contour interval is 10 W/m^2)

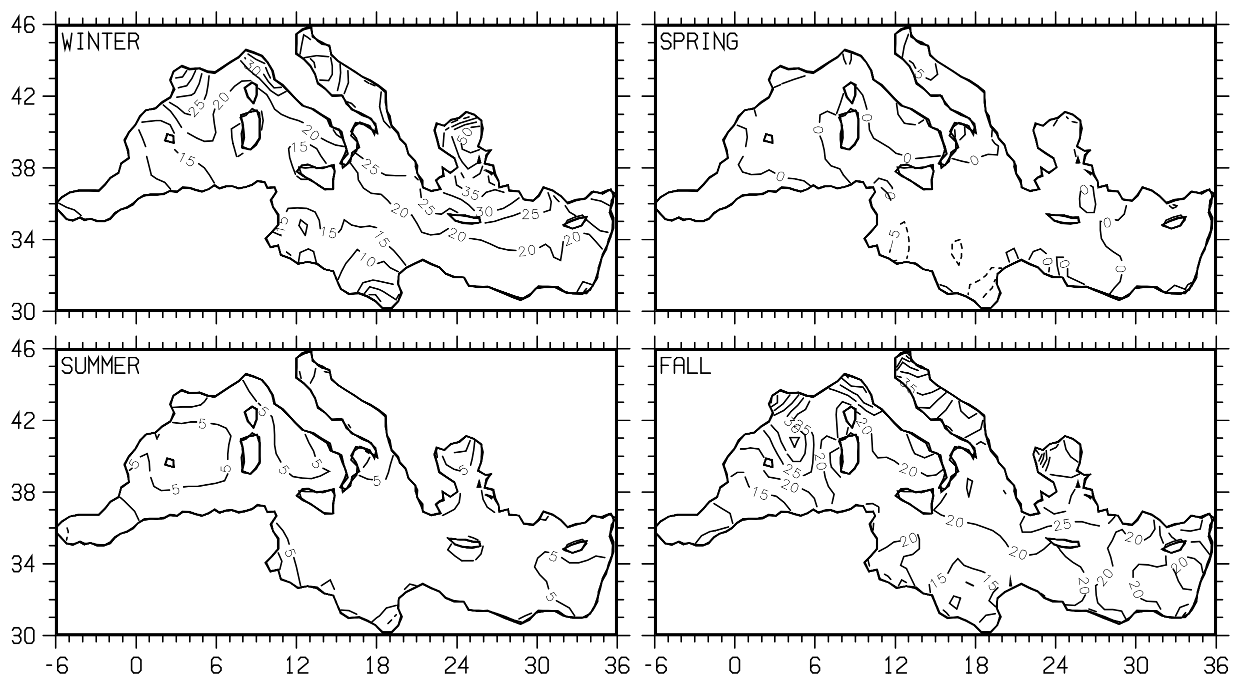

Fig. A7 — Seasonally averaged climatological sensible heat flux (contour interval is 5 W/m^2)

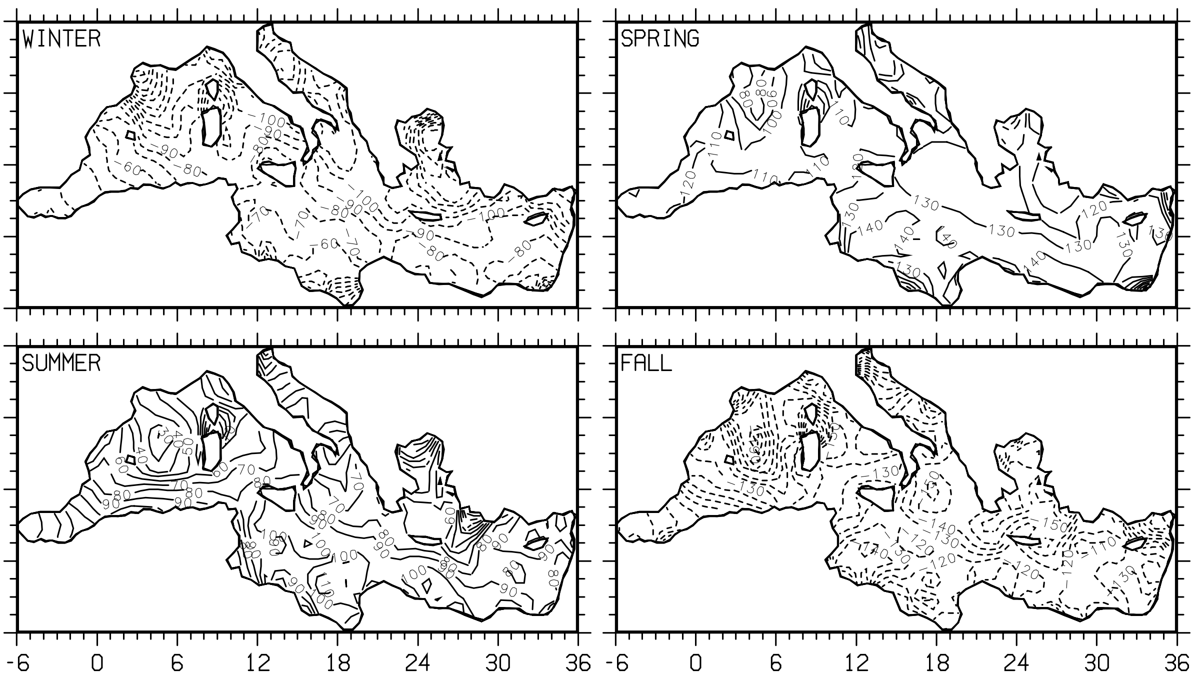

Fig. A8 — Seasonally averaged climatological total surface heat flux (contour interval is 10 W/m^2)

Appendix B

SEASONALLY AVERAGED COAMPS AIR-SEA FLUXES FOR 1999

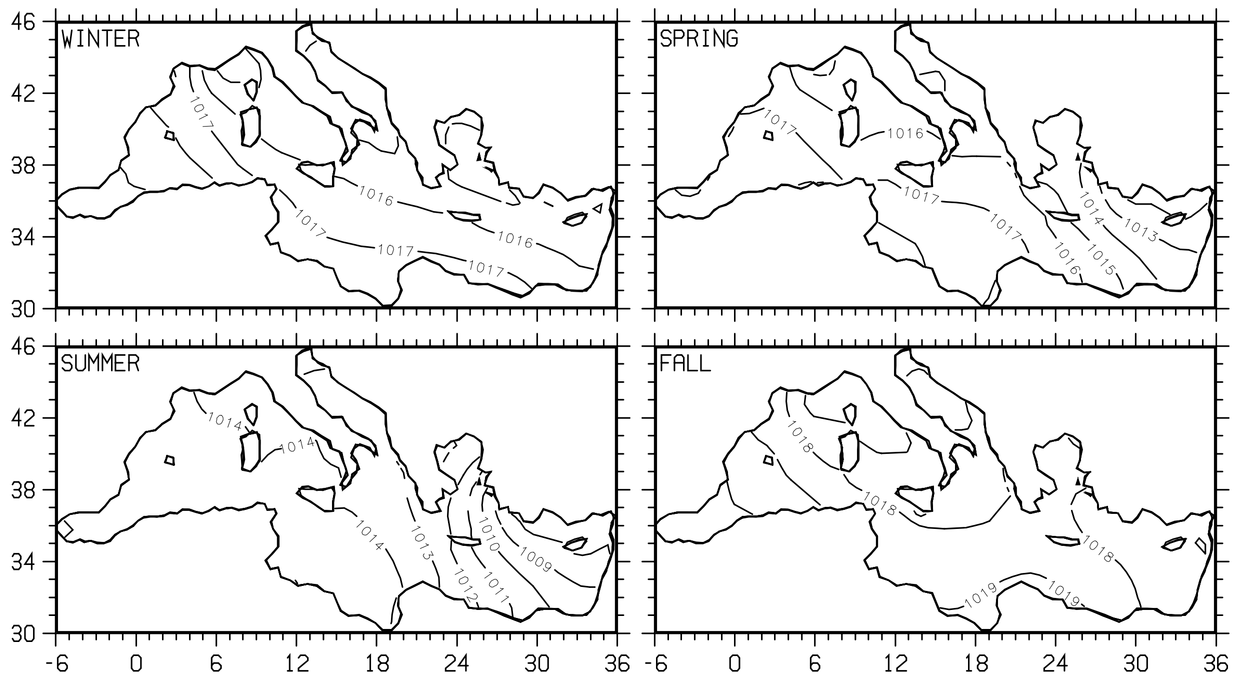

Fig. B1 — COAMPS seasonally averaged surface pressure during 1999 (contour interval is 1 mb)

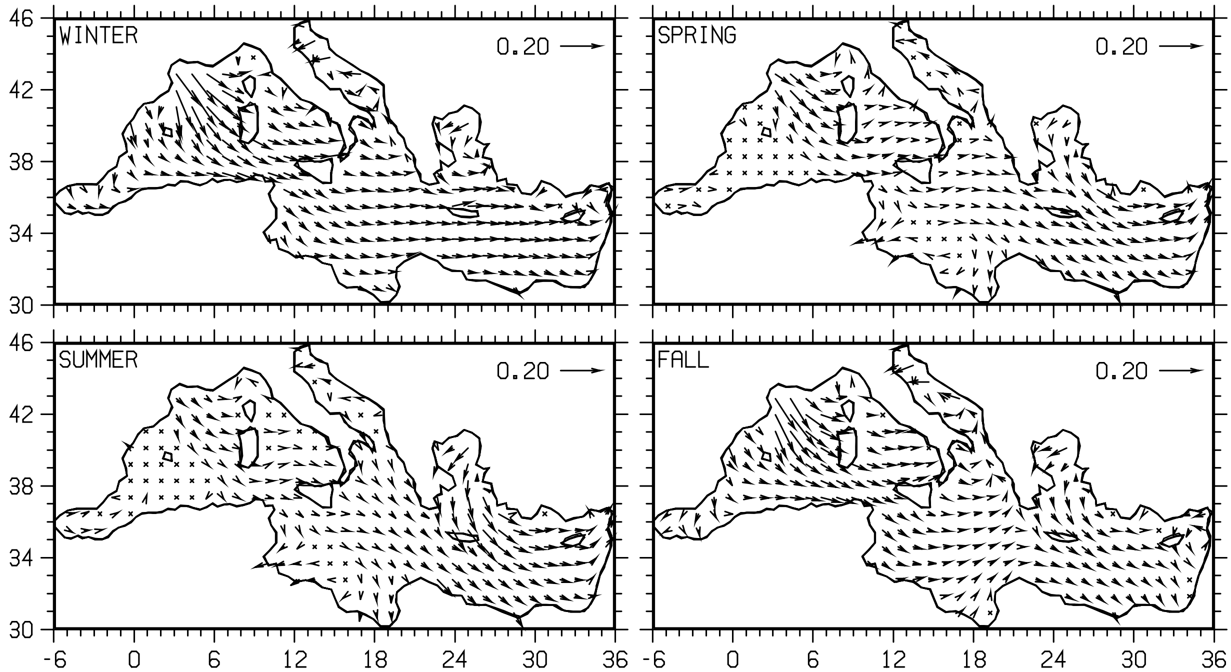

Fig. B2 — COAMPS seasonally averaged surface windstress during 1999 (in Pascals)

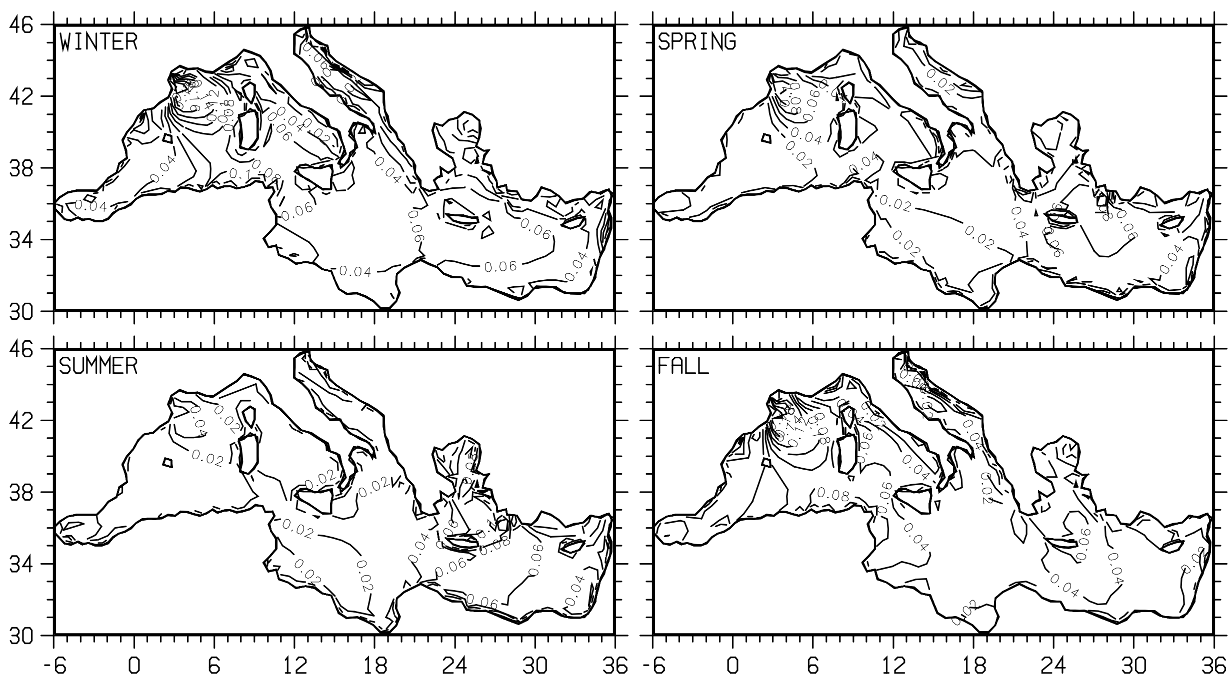

Fig. B3 — COAMPS seasonally averaged surface windstress magnitude during 1999 (contour interval is 0.2 Pascals)

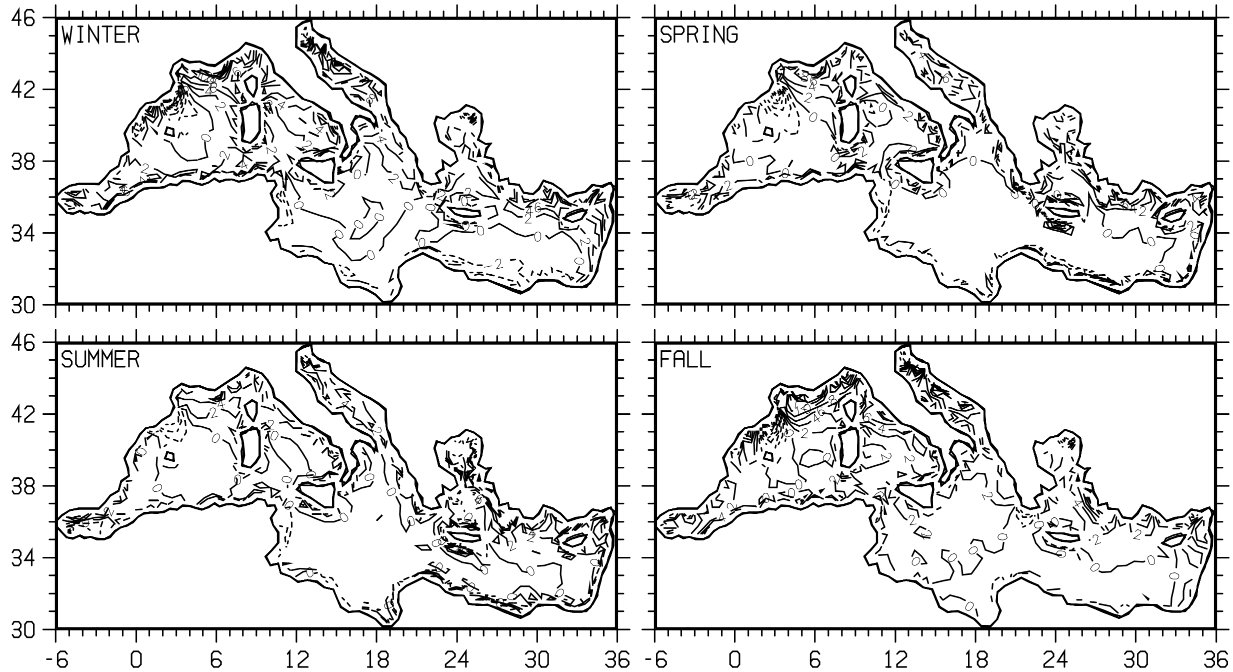

Fig. B4 — COAMPS seasonally averaged windstress curl during 1999 (contour interval is 2 Pascals per 10000 km)

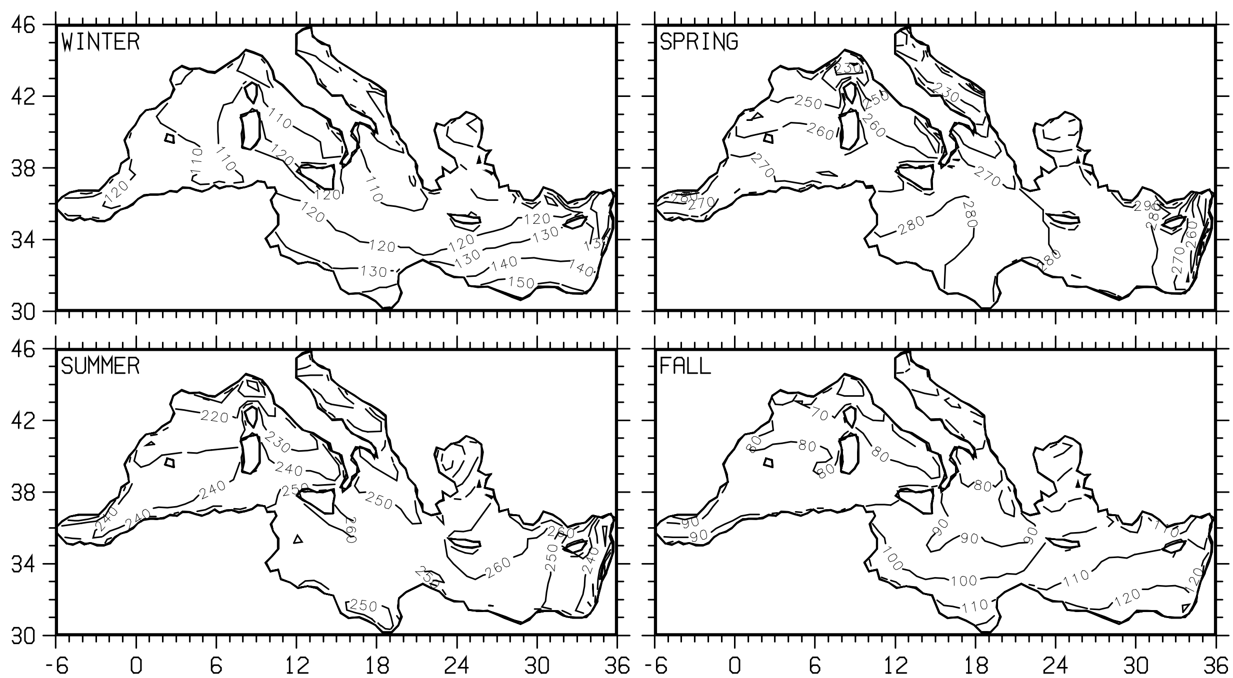

Fig. B5 — COAMPS seasonally averaged solar radiation during 1999 (contour interval is 10 W/m^2)

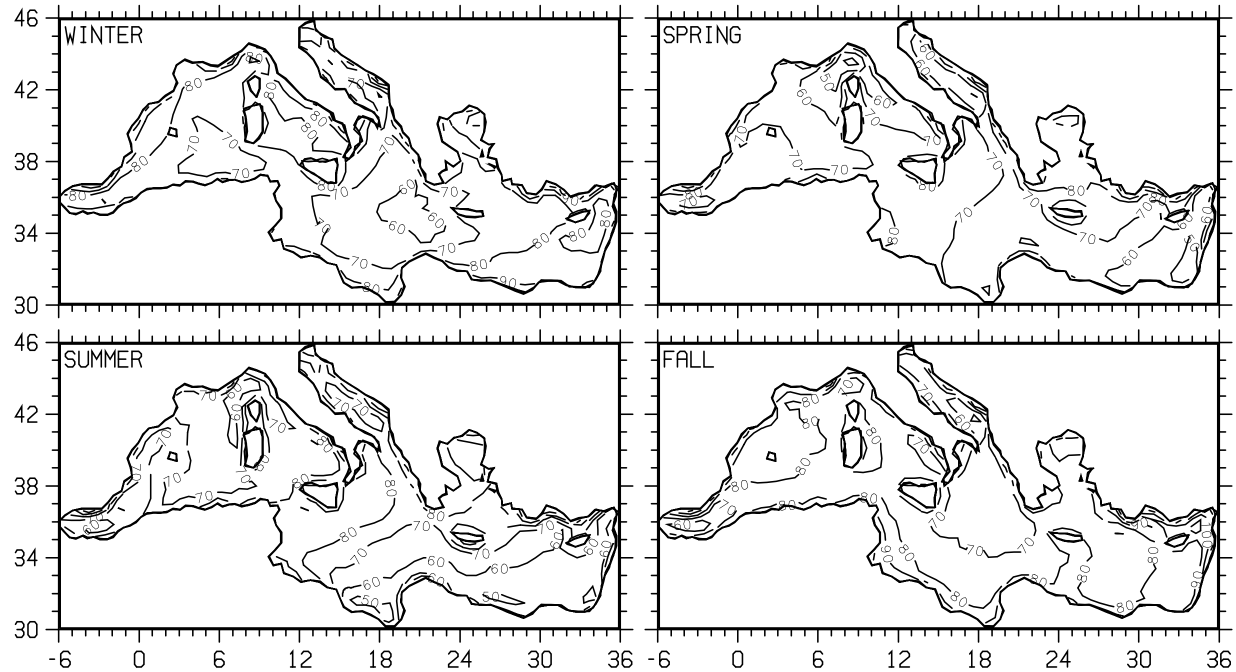

Fig. B6 — COAMPS seasonally averaged longwave radiation during 1999 (contour interval is 10 W/m^2)

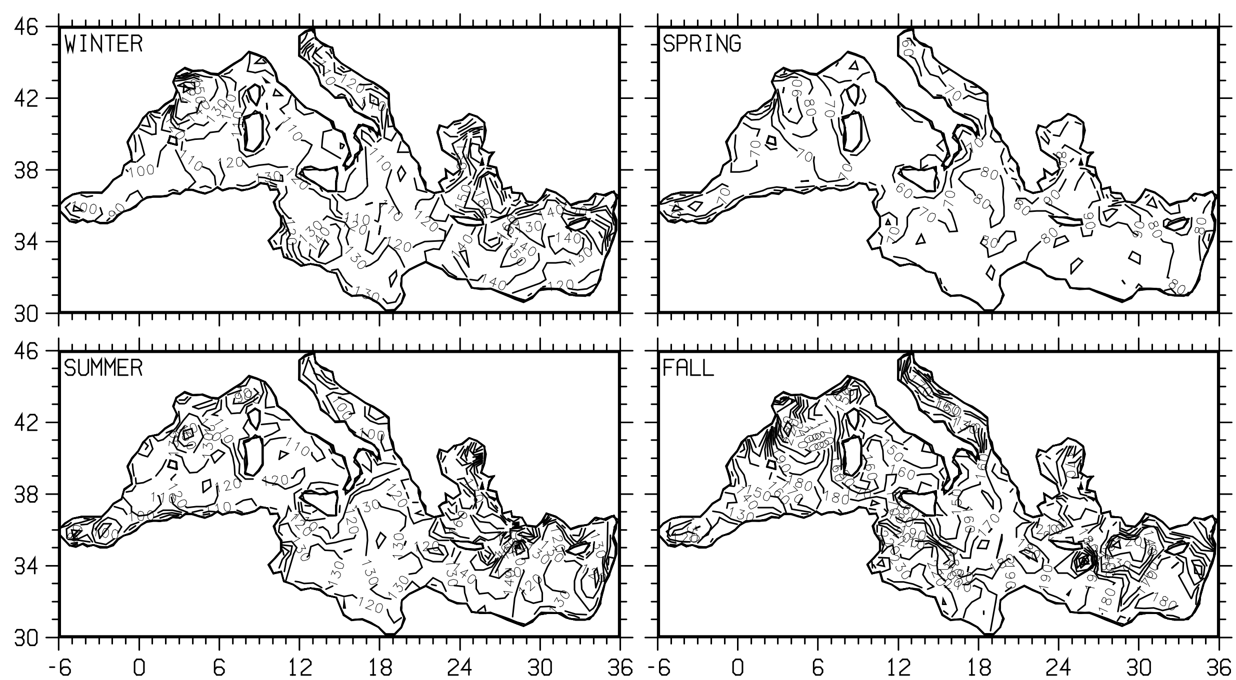

Fig. B7 — COAMPS seasonally averaged latent heat flux during 1999 (contour interval is 10 W/m^2)

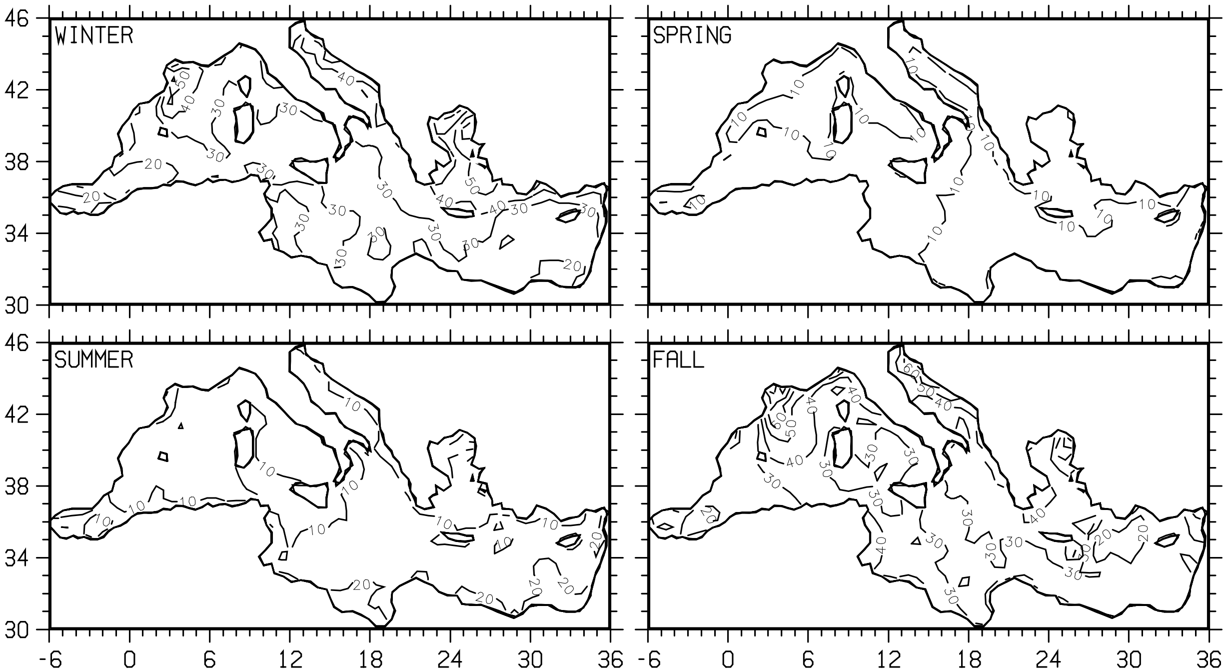

Fig. B8 — COAMPS seasonally averaged sensible heat flux during 1999 (contour interval is 10 W/m^s)

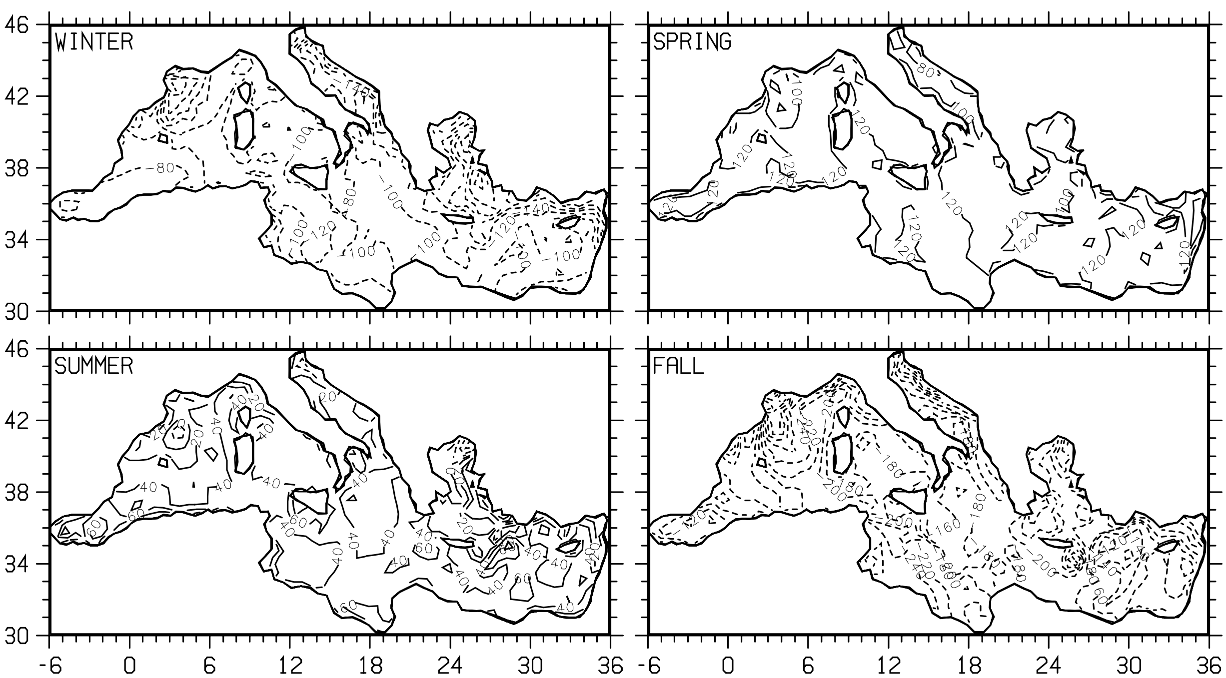

Fig. B9 — COAMPS seasonally averaged total surface heat flux during 1999 (contour interval is 20 W/m^s)

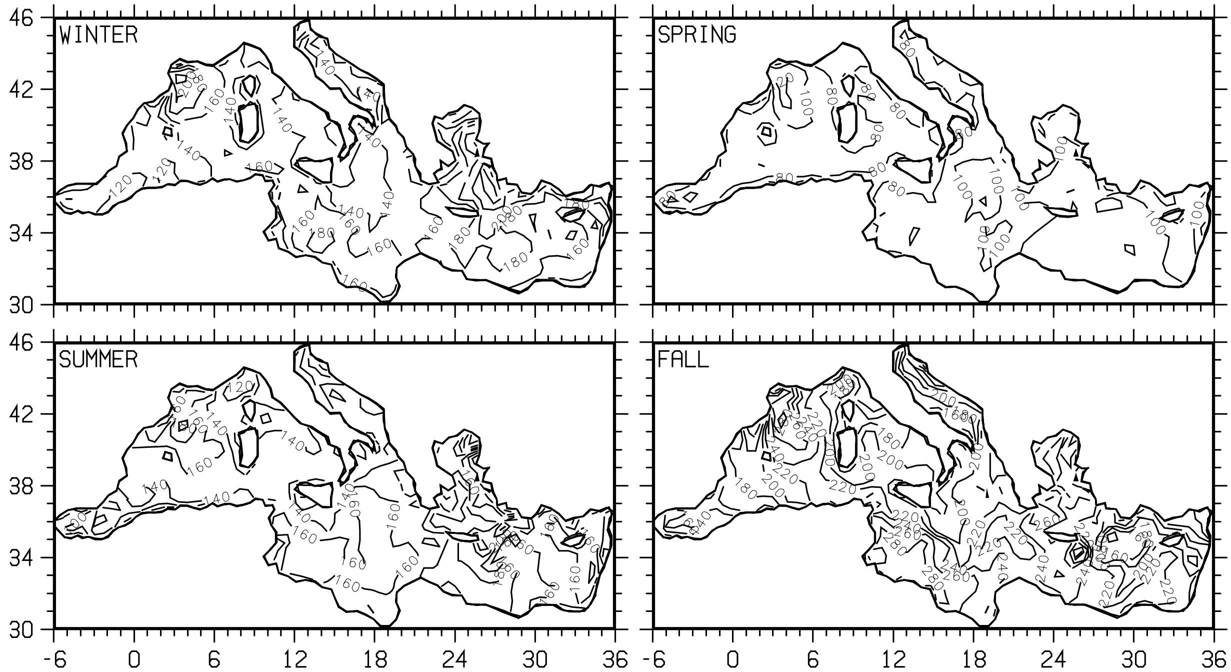

Fig. B10 — COAMPS seasonally averaged evaporation during 1999 (derived from latent heat flux) (contour interval is 20 cm/yr)

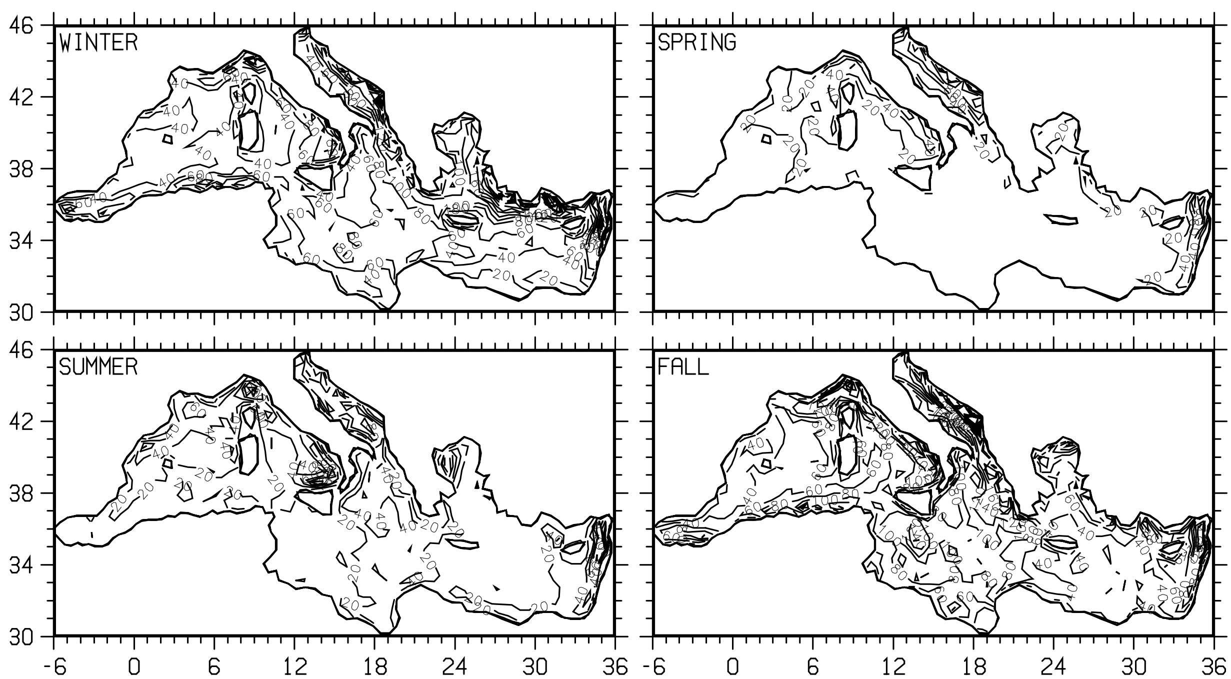

Fig. B11 — COAMPS seasonally averaged precipitation during 1999 (contour interval is 20 cm/yr)

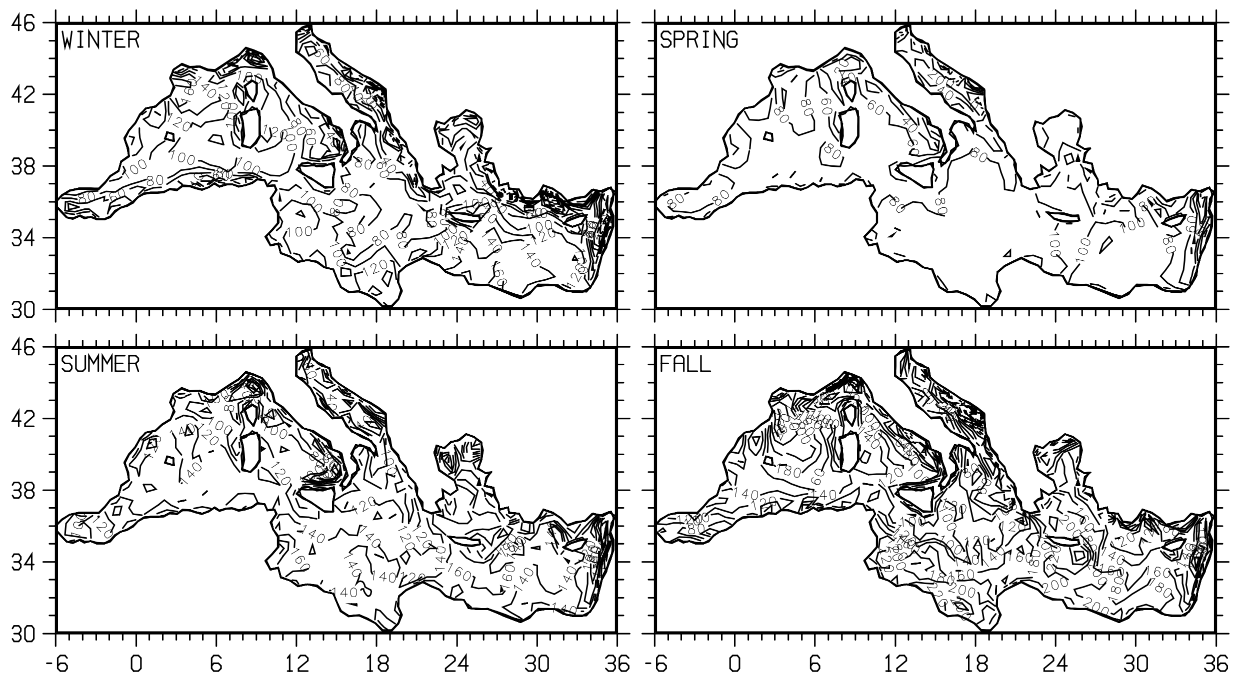

Fig. B12 — COAMPS seasonally averaged surface moisture flux (evaporation minus precipitation) during 1999 (contour interval is 20 cm/yr)

Appendix C

SEASONALLY AVERAGED LATENT AND SENSIBLE HEAT FLUXES COMPUTED FROM COAMPS ATMOSPHERIC FIELDS WITH BULK FORMULAS

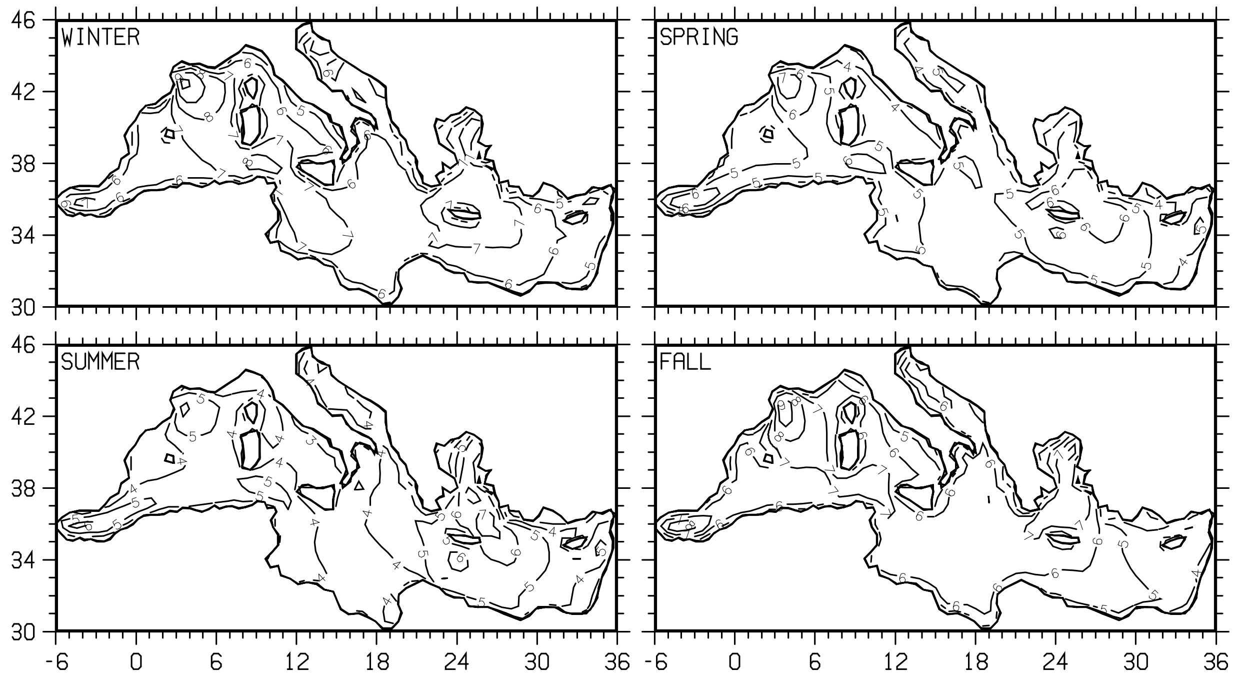

Fig. C1 — COAMPS seasonally averaged 10-m wind speed during 1999 (contour interval is 1 m/s)

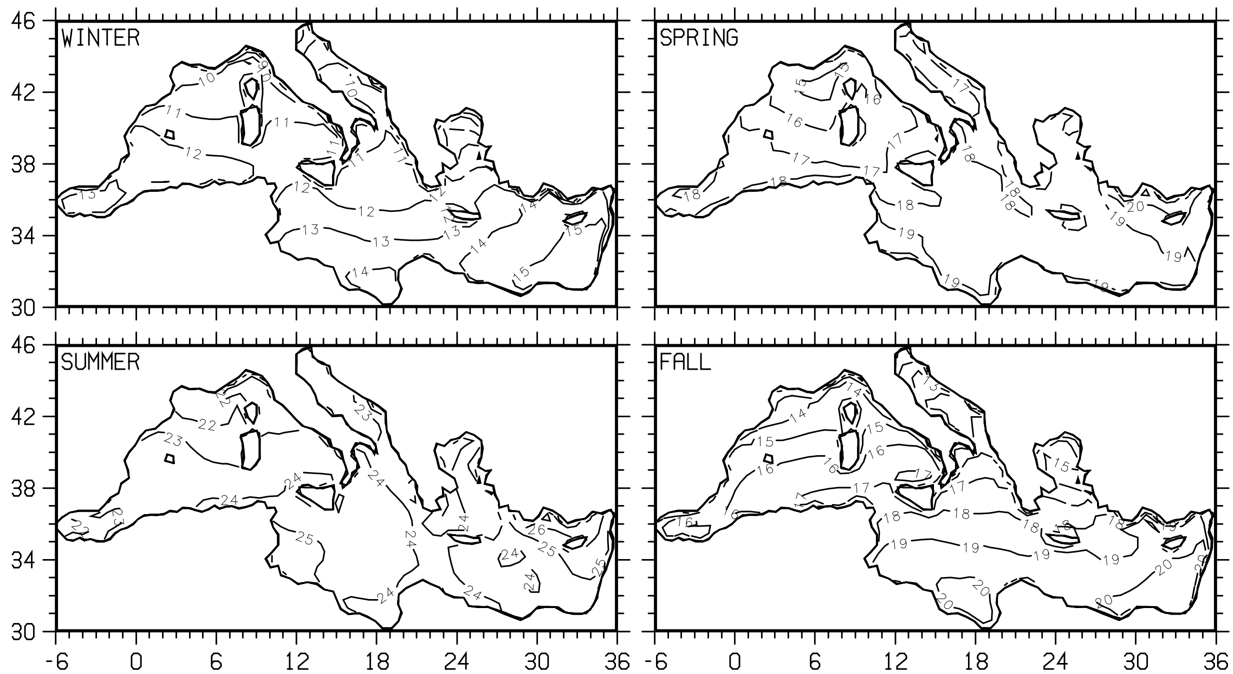

Fig. C2 — COAMPS seasonally averaged 2-m air temperature during 1999 (contour interval is 1°C)

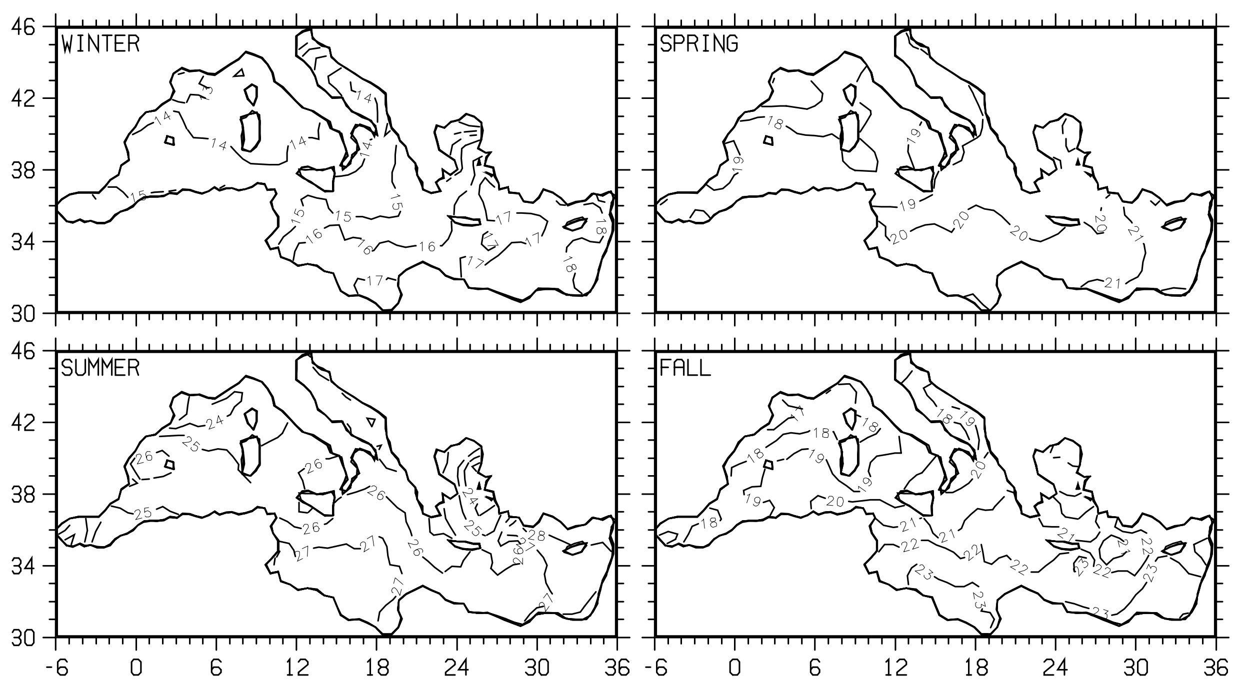

Fig. C3 — COAMPS seasonally averaged SST during 1999 (contour interval is 1°C)

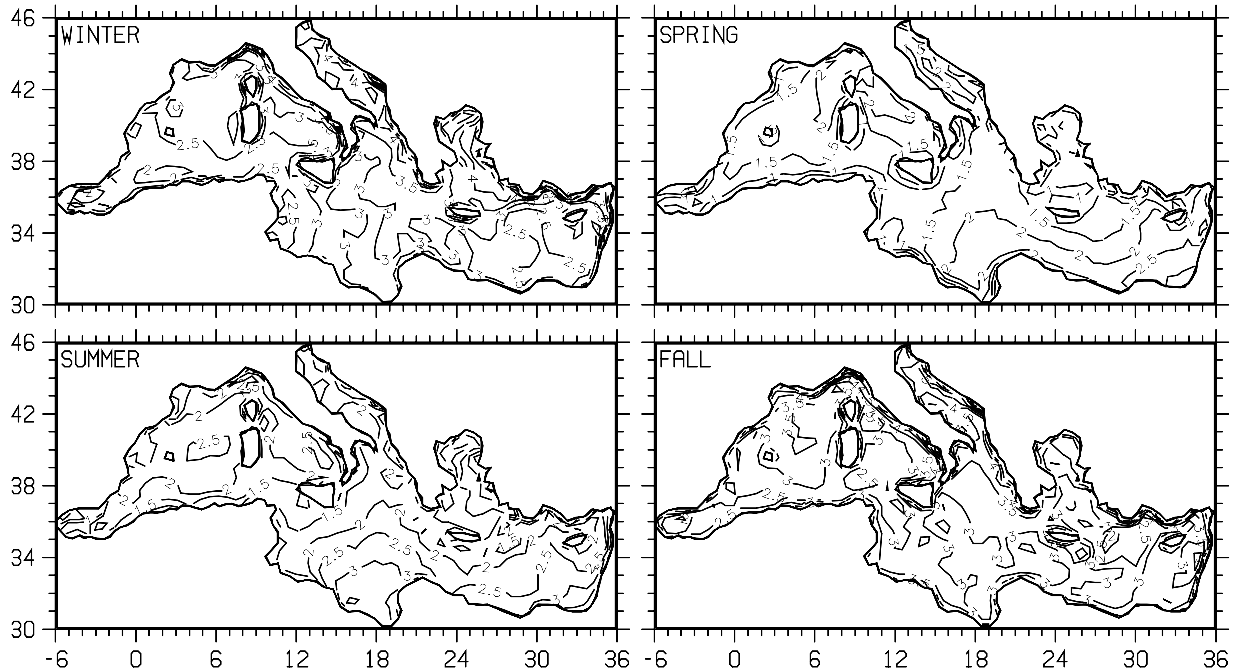

Fig. C4 — COAMPS seasonally averaged sea-air temperature difference during 1999 (contour interval is 1°C)

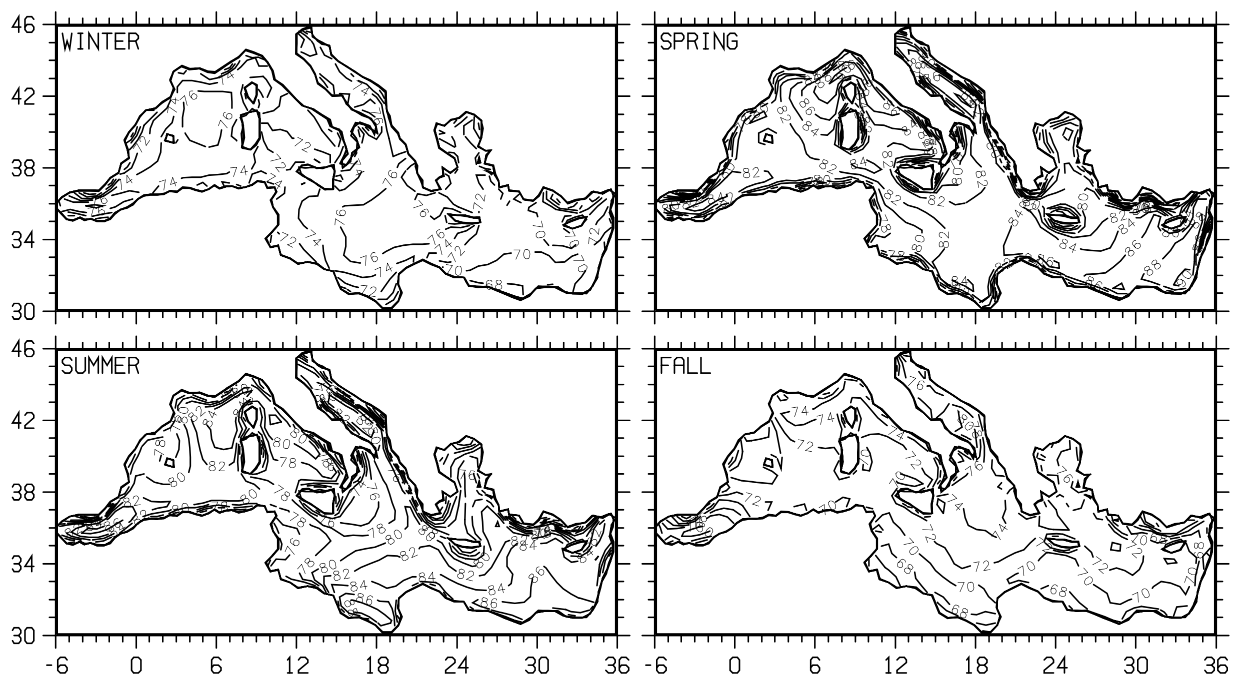

Fig. C5 — COAMPS seasonally averaged relative humidity at 2 m during 1999 (contour interval is 2 %)

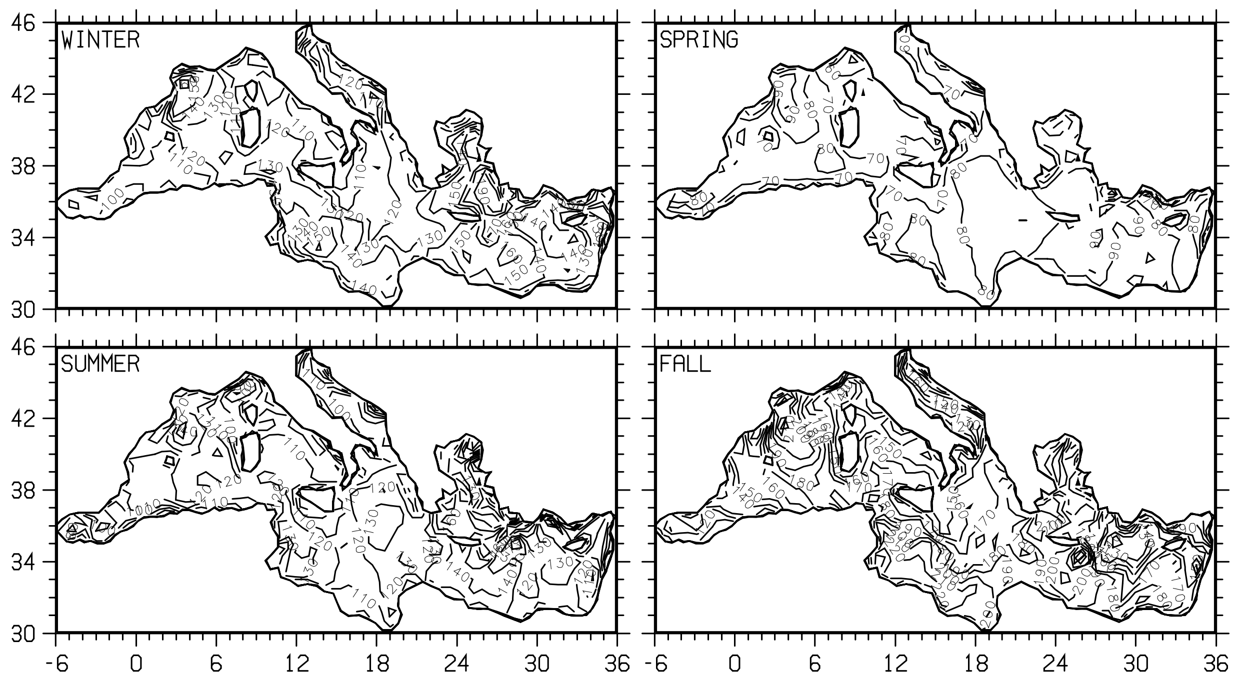

Fig. C6 — Seasonally averaged latent heat flux during 1999 calculated using bulk formula and COAMPS atmospheric fields (contour interval is 10 W/m^2)

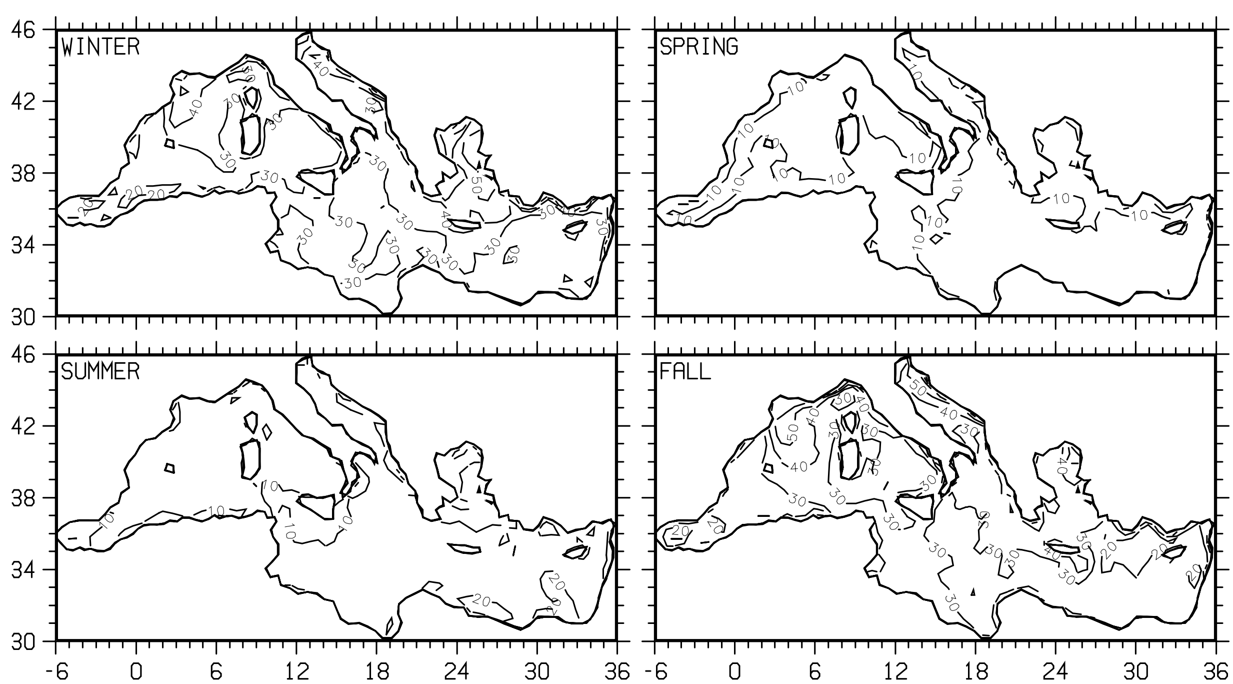

Fig. C7 — Seasonally averaged sensible heat flux during 1999 calculated using bulk formula and COAMPS atmospheric fields (contour interval is 10 W/m^2)